AN INTRODUCTION TO SEDIMENTARY PETROGRAPHY

H. B. MILNER, M.A., D.Sc., F.G.S., A.M.I.P.T.

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SEDIMENTARY PETROGRAPHY

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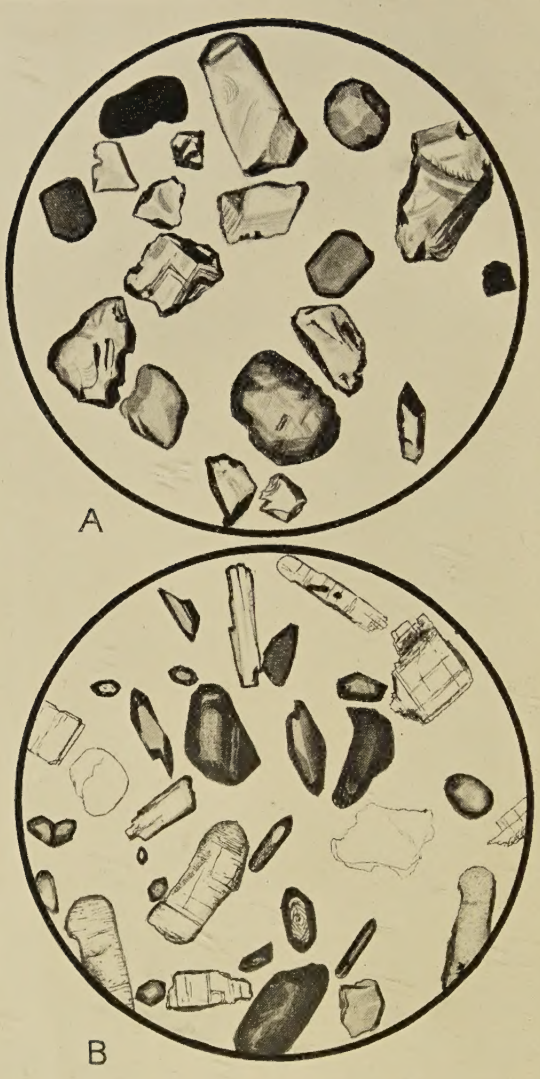

GRAINS FROM ASPHALTIC SANDSTONE, ANGOLA.

A. Magnetic Separation. Ilmenite, Tourmaline and Garnet. [x 50.]

B. Non-magnetic Separation. Rutile, Zircon, Sillimanite, Kyanite. Muscovite. [x 50.]

Frontispiece.]

AN INTRODUCTION TO

SEDIMENTARY PETROGRAPHY

With special reference to Loose Detrital Deposits and their Correlation by Petrographic Methods

By

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PREFACE.

This book has been designed to meet the requirements of all those engaged in the study of microscopical examination of sediments—more especially incoherent detrital deposits—whether for academic or economic purpose. The plan adopted is much the same as that forming the basis of a course of lectures in Sedimentary Petrography (as applied to Oil Technology) given by the author at the Royal School of Mines, and as many of the methods involved are new, not in principle but in application, it is thought that a useful purpose may be served by presenting them in a concise form to a larger audience.

The application of Sedimentary Petrography to certain branches of pure and economic geology, the gradual evolution of the higher technique involved, and the parts played by British geologists in laying the foundations of the subject, are sufficiently discussed in the Introduction which follows, rendering further remarks in connexion therewith unnecessary. At the outset, however, it is desirable to emphasise the fact that, as with other branches of natural science and their technical applications, no degree of finality can be said to have been achieved, and an enormous amount of research, both in the field and in the laboratory, awaits prosecution.

Petrographic methods as means of correlating loose detrital sediments (with which this volume is largely concerned), constitute a factor of the greatest possible import in practical geology. While it has been the author's aim to present this application both in principle and in method, it has been equally his duty to indicate, partly directly and partly by inference, the wider potentialities of the subject and the trend of ulti-

mate inquiries likely to lead to far-reaching results, both from the purely scientific and from the economic points of view.

As its title implies, the book is intended to serve simply as a general introduction to the subject and its applications. A working knowledge of elementary crystallography and optical physics is assumed, this being an essential preliminary to all petrographical studies. In this connexion such standard works as Dana's " System of Mineralogy " or Iddings' " Rock Minerals " should, if necessary, be consulted.

The author desires to record his indebtedness and thanks to his friend, Mr. G. M. Part, M.A., F.G.S., for undertaking the arduous task of reproducing the many detrital mineral grains and diagrams embodied in the book. Mr. Part not only made himself responsible for all the illustrations, but he assisted the author very considerably in the difficult task of selecting the most representative grains for reproduction.

To Dr. H. H. Thomas, Sc.D., V.P.G.S., the author's thanks are due for the loan of and permission to reproduce grains from the hypersthene concentrate from Santa Cruz (*Fig.* 12) and the magnetite, etc., from Hinksford, Staffs (*Fig.* 16), the latter originally described by Mr. J. B. Scrivenor, M.A., F.G.S. [Min. Mag., vol. xiii., p. 351].

The author's thanks are also due to Mr. A. Brammall, M.Sc., D.I.C., F.G.S., for kindly reading the proofs of Chapter II. and for presenting the material from which certain anatase grains were drawn (*Fig.* 2).

Finally, to Mr. G. S. Sweeting, Royal School of Mines, for reading the proofs, indexing and many valuable suggestions, and to Mr. G. H. Freeman (Messrs. T. Murby & Co.) for the painstaking care with which he guided the book through the press, the author tenders his grateful thanks.

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SEDIMENTARY PETROGRAPHY

INTRODUCTION.

The intensive study of sedimentary petrography is a comparatively recent development of geological science, and one which bids fair to play a most important rôle in future stratigraphical research. This branch of natural science claims attention not only on account of an obvious academic value, but because its application to many phases of economic geology is gradually being sought and perfected.

The principles and methods involved are peculiarly apposite to the more theoretical aspects of oilfield development where, for example, correlation of subterranean strata has frequently to be made entirely on the strength of the slender evidence afforded by well sampling.

More and more as new petroliferous areas are opened up are the claims of sound geological investigation of properties being recognised, and just as the application of microscopy has proved an invaluable asset to many branches of industrial geology, so is it fast becoming an important factor in modern oil-land development.

The study of microscopical organisms—chiefly foraminifera and algae—in petroliferous deposits, has during the last few years been carried on assiduously in many of the Tertiary oilfields of the world. It was hoped by this means to formulate a basis of identification and correlation of oil sands and their enclosing strata, thus providing results at once stratigraphically and structurally significant. Largely owing to the tendency of many of

these organisms to have a wide distribution in space and time, the results, in so far as correlation within narrow limits is concerned, have not been as encouraging as was at first anticipated. Nevertheless, some important stratigraphical data have been obtained in this way from rocks either poor in the larger and more easily recognisable fossils, or, if fossiliferous, in cases where the drilling system employed has inhibited, by comminution of the shells, their preservation in the well samples. Under these circumstances a comprehensive study of the mineralogical composition of the deposits with which oil is associated, seemed to offer, from first principles, great practical possibilities, and it was but a step to adapt the hitherto purely academic study of sedimentary petrography to the technical requirements in view.

The work of Mr. V. C. Illing, in Trinidad, in 1915, clearly showed the great economic value attaching to a detailed study of the highly disturbed and rarely fossiliferous oil-bearing strata in the southern part of the island; the recognition of successive groups of sediments characterised by exclusive mineral assemblages constituted a new weapon of attack on problems of correlation which had hitherto defied solution, and one which has since given most encouraging results.

More recently, the author's researches on the correlation of isolated Tertiary deposits in Western Cornwall have demonstrated even wider applications of these principles than were initially anticipated, and results of similar work in other areas, especially where local, though complex, geological structures prevail, have proved equally conclusive.

In another direction, this applied branch of science has furnished some important information with regard to the types of sand best suited to glass-

making, foundry work, building purposes, etc. In this application Professor P. G. H. Boswell has, by his detailed studies of the sedimentary rocks of this country, given us results of the utmost industrial import, and future work along these lines may be expected to aid the solution of many of the problems involved in the widespread use of refractories in the arts, especially in cases where difficulties are being constantly met with as a result of the adoption of purely empirical processes. This phase of study comprises not merely mineralogical, but chemical and mechanical analysis, and estimations of the degrees of permeability and porosity of the sediment, all of which factors have, incidentally, a special significance for the petroleum geologist and engineer.

On the purely academic side, the tendency has been in the past mainly towards research in the subject for its own sake, with little or no regard for its broader potentialities; the sampling of a particular sediment, the segregation of its "heavier" and more stable constituents and their ultimate mineralogical analysis, formed a fascinating change from the investigation of thin sections of more compact rocks, and one which was followed mainly because it was, indeed, a new departure in experimental petrology. This narrowness of treatment, however, was destined to be rapidly transgressed, and one by one investigators became imbued with the broader potentialities of the subject, when it was realised to what extent fundamental problems in stratigraphical geology were capable of solution along these lines. Questions concerning the genesis of a sediment—involving not only ideas as to its source of origin, but also definite conceptions of its mode of transport and deposition, the nature of climatic and kindred conditions at the epoch

of its formation—together with the pertinent aid which the subject affords to palæogeographical restoration—are all embraced by systematic petrographic examination of a series of deposits. It is not difficult, therefore, to appreciate the reasons underlying the rapid evolution, such as has taken place within the last twenty years or so, of a science engendering so many far-reaching possibilities.

The foundations of the subject were undoubtedly laid by Sorby, whose work and publications (especially his two presidential addresses before the Geological Society in 1879 and 1880) are now classical. Later, in 1887, Mr. A. Dick recorded his observations on the Bagshot Sands of Hampstead, which included a description of the heavy mineral constituents; in this year also Sir Jethro Teall published certain methods bearing on the examination of sediments, while three years later Hutchings contributed an important paper on the subject.

In 1895 Retgers investigated the dune sands of Scheveningen, Holland; his work was certainly on modern lines and a distinct advance on that of his predecessors. Dr. Mackie next contributed to the advancement of the science by his researches on the Sands and Sandstones of Eastern Moray, published in 1896, and by a masterly consideration of the mechanical factors involved in the rounding of sand grains, published in 1897. The year 1900 saw the publication of Professor T. G. Bonney's paper on the Bunter Pebble-Beds of the Midlands, in which he dealt with their petrography, mode of transport and their possible sources of origin, while the subsequent researches of Dr. H. H. Thomas, published in 1902 and again in 1909, marked a very definite advancement both in method and interpretation of results. More recently still, several

workers have contributed to our knowledge of sedimentary deposits, particularly Messrs. Boswell, Crook, MacDonald Davies, Gilligan, Illing and Rastall, whose combined teaching has done much to widen the scope and potentialities of the subject. [See Bibliography, p. 112.]

Attention is specially drawn to two papers of outstanding merit which should be carefully read by all students of sedimentary petrography in its broadest applications; both are presidential addresses delivered before the Geological Society of London, one by Professor J. E. Marr in 1905 on the "Classification of Sediments," the other by Professor W. W. Watts in 1911 on "Geology as Geographical Evolution."

In the former paper an analogy was drawn between meteorograms, as recording meteorological variations, and "geograms," a word used by Professor Marr in place of the expression "Geological Column," and connoting, principally, variations in lithology and in organic assemblages that could be traced in a deposit, if a column obtainable from boring right through it were to be laid flat and studied from one end to the other. Although purely a hypothetical conception, the "geogram" is the ideal to which all petrographic investigations should tend, and even though the tracings are broken or discordant, as they are bound to be, the evidence will be none the less valuable and suggestive.

Professor Watts has enlarged this conception in the following words:—

"In order to obtain what Dr. Marr has called the 'geogram' of a formation in its greatest perfection, we require to know the entire extent of its variations, not only along its outcrop, but in that part which is hidden from sight; and we ought to

be in a position to infer the probable variations in that almost equally important part which has been destroyed by denudation."

In a very suggestive article in the Geological Magazine for March and April, 1916, Professor Boswell discussed both the theoretical and practical tenets of the science, and their bearing on the progress of stratigraphical research. He has, in fact, given a very succinct account of the methods by which Professor Marr's " geogram " of a formation may be best attained, and the article is valuable for the co-ordination of facts and constructive criticism of hypotheses which it presents.

There is, however, the danger that, notwithstanding these careful expositions of first principles, the purely analytical phases of the subject may assume an undue prominence out of all proportion to their actual worth; it is useless amassing quantities of facts without seeking to reconcile them with some hypothesis capable of explaining their significance, thus contributing to the development of the science; if theory lags behind practice, the result must inevitably be to retard rather than to advance the process of evolution, no matter what branch of natural science is engendered.

It is therefore necessary at the outset to stress the importance of the more fundamental aspects of sedimentary petrography, in particular the influence that its study must have on the progress of geological research. The fact that the major part of this book concerns itself with descriptive mineralogy should in no way cloud the true perspective of the subject; the determination of the mineral constitution of sediments is but a means to an end, it is the first stage towards unravelling their history.

CHAPTER I.

NOTES ON THE SAMPLING, TREATMENT AND MICROSCOPICAL EXAMINATION OF DETRITAL SEDIMENTS.

It is not proposed to give here an exhaustive account of the various methods devised for the treatment of detrital sediments prior to their microscopical examination; these have been adequately discussed by Mr. T. Crook [26]†, and more recently by Dr. Holmes [44], to whose works the student is referred for full details. It may be useful, however, to outline the methods employed by the author during the course of his work on the study and correlation of sediments, from the initial sampling of a deposit to its ultimate analysis, noting, especially, difficulties which often arise and methods employed for overcoming them.

1. *Sampling.* Comprehensive sampling of a given sediment is at the outset a matter of great importance and one requiring systematic practice and care. Extensive deposits can only be satisfactorily sampled providing that there are numerous natural and artificial exposures accessible; this will obviously vary with the nature of the country in which investigations are being carried out.

Surface sampling, as distinct from vertical or depth sampling, should be effected at equal intervals along and transverse to the strike of the beds, such intervals depending on the extent of the

† Numbers in square brackets [ ] refer to references in the bibliography, p. 112.

deposit, persistency of lithological facies, and topographical considerations. Sampling in vertical sections exposed by quarries, cuttings, etc., involves collecting material from horizons determined primarily by change of lithologic facies and of texture of the rock. Where vertical sections are absent, samples collected superficially (unless the beds possess a marked regional dip) can only represent a very average composition of the horizon outcropping, and will in themselves be no criterion of the nature of the concealed beds; under such conditions "pitting" may be necessary for the production of samples within twenty feet of the surface, depending on local conditions, or failing that, a portable boring apparatus must be employed. For sampling in depth (over fifty feet), the geologist has to rely entirely on material taken from deep borings (oil, water, etc.), and the efficacy of such sampling will depend largely upon the system of drilling employed. Abrasive methods normally yield core samples, and these are the most valuable and easiest to deal with from the geological standpoint. Percussion methods (cable-tool or pole-tool system) are especially adapted to oilfield requirements, and sampling, by means of a bailer, can usually be carried out. The hydraulic rotary method of drilling for oil (now widely adopted) unfortunately precludes all chance of obtaining uncontaminated samples, notwithstanding frequent assertions to the contrary.

Samples of incoherent material, such as sand, can most conveniently be collected in the field in small numbered canvas bags, each capable of holding about 200 grms. of material. Care should be taken to record the precise locality and horizon from which the sample is taken. In collecting from a given exposure as, for instance, from a bed of

sand three feet in thickness, and in order to obtain as representative a sample as possible from this bed, the bag should be held against the face and at the bottom of the bed, and a geological hammer used to remove material by drawing it from the top of the bed downwards, the dislodged sand thus falling into the bag. Where there are several feet of rock exposed, this method can be repeated from one horizon to another, providing that the whole section is accessible. Surface sampling involves in each instance the taking of small amounts of material from proximate points to make up one sample which shall be representative of the particular locality chosen, providing that some degree of homogeneity of deposit be in evidence; rapid lateral variation will necessarily narrow down the limits within which this form of sampling may be safely employed.

Plastic rocks, such as clays, obviously do not lend themselves to the foregoing methods of sampling, the material usually having to be cut out with a knife. It should be borne in mind that much larger samples of clay are required than in the case of sand, also that *the coarser the sand, the larger the sample necessary*, if reasonable yields of "heavy" residue be sought. Compact, consolidated sediments must be hammered out in the usual way, the material being subsequently crushed prior to treatment [61].

2. *Treatment of Incoherent Detrital Material. Sands and Silts.* The sample in the first place should be examined with a hand lens for the detection of the larger and more easily identifiable minerals, and for those which may be destroyed by subsequent treatment with acid; such minerals as pyrites, limonite and glauconite, together with carbonates and most phosphates are included in the

latter category. A little material should also be mounted dry on a glass slide and examined under the microscope (in a vertical position), both by transmitted and incident light.

Since quantitative data are in all cases desirable, especially for correlation purposes, a portion of the sample is weighed, from 30 to 50 grms. of material being taken, depending on the grade size of the particles. A separation of the larger detritus is effected by using a 30-mesh sieve, and, if desirable, a further rough grading may be obtained in differentiating medium and fine sand and silt by the employment of sieves of smaller mesh, 60, 90 and 120 mesh to the inch (or approximately equivalent metric sieves). Sieving, as Professor Boswell has pointed out, is not an accurate method of grading sediments, and can only be regarded as a convenient means of segregating crops of particles of a mean grade size; where accuracy and precise mechanical analysis are necessary (as is frequently the case), elutriation must be carried out [44].

For rough quantitative comparison of samples, it is frequently convenient to ascertain the percentage proportions of the various grades segregated by sieving, using the 30, 60 and 90 mesh sieves for the purpose, and weighing the amounts of the material obtained. Results may then be expressed as follows:—

+30.....p% (Sand retained by 30-mesh sieve.)
—30+60.....q% (Sand passed by 30- and retained by 60-mesh sieves.)
—60+90.....r% (Sand passed by 60- and retained by 90-mesh sieves.)
—90.....s% (Fine material passed by 90-mesh sieve.)

The authigenous material coating sand grains is removed by gently boiling with water; in most cases the addition of hydrochloric acid (up to 20%) is necessary to complete clarification, though with exceptionally ferruginous material, up to 50% HCl may be necessary. It is, however, advisable to restrict as far as possible the quantity of acid used and also the time of digestion, since partial destruction of certain minerals is inevitable, and in some cases total decomposition or solution may follow, as indicated above; loss from this cause is anticipated by the preliminary examination of the material as suggested.

When the grains are clear they are washed free of acid with cold water, and then dried slowly in a steam-oven or in a sand bath. The material is then weighed again, the difference in weight being the amount of cementing matter or soluble compounds removed by the acid treatment.

The next operation involves the use of a suitable " heavy " liquid for concentrating the mineral particles having a specific gravity greater than 2.88. Of the many liquids advocated and in use, the author favours bromoform (s.g. 2.88 to 2.9, varying considerably in purity) for all general purposes. The objections, that it is liable to excessive convection current effects, rapid evaporation, and that it is expensive to employ, may be met by certain preventative measures. These consist in carrying out the separation in a fume cupboard or constant temperature chamber, or in a room rendered free of warm air currents, also by keeping the bromoform covered when in use with a watch glass which fits the funnel, and taking care to preserve the benzol washings for the ultimate recovery of the bromoform dissolved; further, the price of bromoform cannot be regarded as prohibitive when

compared with the prices of the various other liquids sometimes employed. In the hands of a careful manipulator, 1 lb. of bromoform should be ample for the separation of at least 50 samples, if care is taken to reduce loss to a minimum when recovering the liquid from benzol washings.

The form of apparatus employed is shown in the accompanying diagram (*Fig.* 1), and is self-explanatory. The sand is poured into the upper funnel and constantly stirred, at least half an hour being necessary to ensure a good separation. It is doubtful whether a 100% separation can ever be effected in practice, but with care it should be reasonably complete. Filtering may in all cases be accelerated by using fan-folded filter papers, obtainable from most makers. Both the light and heavy residues are washed free of bromoform with benzol, and subsequently dried either in a steam oven or over a sand bath. The " heavy " residue is then weighed.

Magnetic separation of the " heavy " residue follows, the strongly magnetic species being extracted with a horse-shoe magnet having adjustable pole-pieces, and care taken to place a thin sheet of paper between the poles of the magnet and the residue. Further separation may be effected by using an electro-magnet whose intensity may be varied (within narrow limits) by altering the resistance of the current; in this way moderately magnetic and weakly magnetic minerals may be isolated from both strongly and non-magnetic species.

If it is desired to segregate a particular mineral of given specific gravity from the residue, the use of other liquids may be necessary; those most easily manipulated are methylene iodide (s.g. 3.3) and fused mercurous nitrate (s.g. 4.3); the former

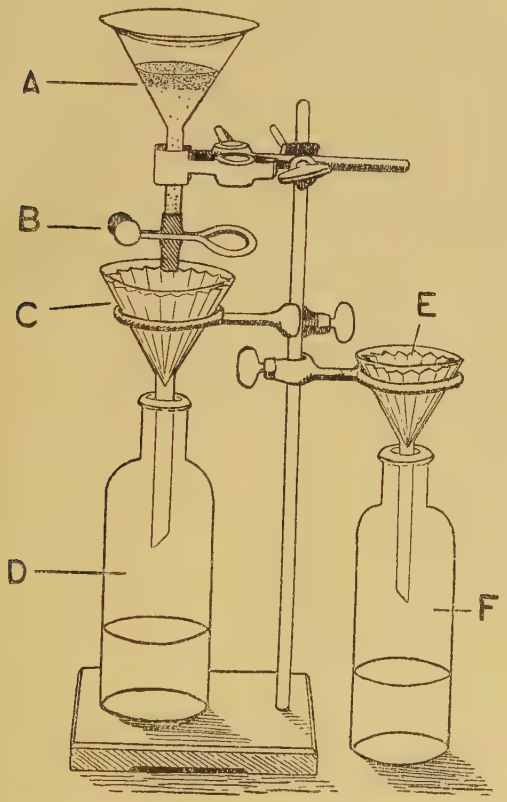

Fig. 1.

A. Funnel containing bromoform and sample from which heavy grains are settling down.
B. Pinch-cock grip on rubber tubing attached to funnel stem.
C. Folded filter paper for holding up residue.
D. Bromoform bottle.
E. Filter to prevent material from entering F.
F. Benzol washings bottle.

necessitates washing with benzol and the latter with water. Methylene iodide separations are most conveniently carried out in a shortened boiling tube, the excess of liquid with the lighter particles being poured off into a small basin; alternatively an ordinary separating funnel may be employed. Mercurous nitrate separations are made in a test tube, the salt and the residue being heated together over a water bath; in the fused state, gravitational separation occurs, the lighter particles (*i.e.* s.g.$<$4.3) floating to the surface of the melt. On cooling, solidification ensues, the tube is broken and the "heavy" mass isolated from the lighter by cutting the salt with a knife. The grains are ultimately recovered by dissolving up the mass in water.

Again, species present in the lighter portion of a sand (s.g.$<$2.88) may be segregated by diluting the bromoform with benzol to the desired gravity.

Where chemical tests are necessary, it should be borne in mind that such tests are only applicable to material in bulk, and that even microchemical reactions are inadmissible with detrital grains. In order to carry out such tests, it is necessary to concentrate the particular species by using suitable liquids of different specific gravities. In some cases a segregation may be obtained by careful manipulation of the electro-magnet or by the employment of electrostatic methods as suggested by Mr. T. Crook [25].

A method devised by the author and one which works well in many cases, particularly with minerals of specific gravity above 3.2, is to place the residue on a sheet of glazed paper and tap the paper gently with a pencil or other implement capable of imparting a satisfactory frequency to it. An improved method is to use a thin metal plate

(copper or tin) supported by an iron clamp from a retort stand; the period of vibration of the plate is previously determined by trial and then a suitable tuning fork of the same frequency selected to induce the necessary resonance. It will be found in both cases that a good separation can be made, though a certain amount of practice is necessary to ensure success. Once isolated, it is often found advisable to subject a few grains of the concentrate to refractive index determination by means of standard liquids of known refractive index; such a course gives valuable diagnostic evidence. The most generally useful refractive index liquids are water (1.434), olive oil (1.469), xylol (1.500), bromoform (1.589), carbon disulphide (1.628), and methylene iodide (1.740). For further liquids employed, refer to Holmes [44]. Other physical or mechanical tests on the concentrate can also be made, if necessary, prior to chemical investigation.

Mounting of Grains for Microscopical Examination. It is advisable to mount the total residue for microscopical examination; by so doing, risk of losing rare species is minimised. The different magnetic crops are mounted separately, and a representative sample of the lighter material also mounted. Glass microscope slides (3in. x 1in.) and thin glass cover slips (1in. x 7/8in.) are the most useful sizes, the mountant being hot Canada balsam. Non-permanent mounts may be made by using ordinary cedar oil, R.I. 1.516.

The exclusion of air bubbles may occasion some difficulty at first; the process is aided by moistening the cover slip with turpentine before pressing it down on to the slide; this may be varied by putting the grains on to the moistened cover slip and then pressing it down on to the slide on which the balsam is sufficiently heated. A little

careful " to-and-fro " motion imparted to the cover slip with tweezers, while the balsam is still hot, is often all that is necessary to obviate the presence of such bubbles.

Solution of the surplus balsam is rapidly obtained by using methylated spirit or benzol, a final immersion of the slide in ether being advantageous, but not necessary. Xylol is probably the quickest solvent, but it has an unfortunate habit of eating into the balsam under the cover slip and thus impairing the mount.

Clay. Clay, marl, extremely fine silt and similar material require substantially different treatment from that involved in the case of coarser detritus. Some examples, when dry, are extremely difficult to " break down " under water, though a few drops of ammonia or 2% solution of Na_2CO_3 may be effective in this respect. Professor Boswell has described a neat method of making the sample practically red-hot, and then plunging it into cold water, to obviate the difficulty; but even this is not always successful, and a very gentle pulverisation in a mortar may be necessary.

An initial concentration may be obtained by repeated washing with water, in much the same way that panning of sands is carried out; the resulting material may have to be cleaned with weak acid, but in many instances this proves unnecessary. When dry, a bromoform separation may be tried, and if the grains are not too small, it may be partially successful. The author has found, however, that a sample composed of grains of average grade size 0.01 m.m. or less, will not respond to this treatment, and in such cases recourse has had to be made to other methods. A somewhat tedious way is to mount up several slides of the concen-

trated material and differentiate under the microscope between the essential and accessory minerals; or elutriation may be resorted to, in order to produce a series of graded crops of minerals which may be mounted for examination under the microscope. It is frequently found that concentrations of the " heavy " minerals occur with two or three definite grades, and this facilitates their study. The fact that a mechanical analysis of the sample is obtained at the same time is again often an inducement to employ this method.

Identification of extremely small mineral particles is greatly helped by employing a 1/12th oil-immersion objective, using cedar oil as the temporary mountant.

Calcareous Rocks. Apart from the production of thin sections of calcareous rocks, the isolation of the insoluble residue (if present) is frequently a matter of petrological importance. The usual method is to break up the sample and pulverise gently in a mortar. The material is then washed in water and finally digested with 20% HCl solution until only the residue is left. By weighing before and after the acid treatment, the percentage of insoluble material may be obtained, this material being used both as a qualitative and quantitative basis of comparison of samples.

Compact Rocks. Compact, consolidated sediments such as sandstones, grits, quartzites, shales, mudstones, ironstones and the like, are normally studied by means of thin sections cut from the samples, as with igneous rocks. But just as the minor accessory minerals frequently escape detection in thin sections of the latter, so it is with sedimentary types, and for this reason the supplementary practice of microscopical examination of the crushed material is recommended.

The methods, applicable alike to igneous and sedimentary rocks, consist in crushing the sample in a steel mortar until completely pulverised. The powder is then panned in water in a 10-inch evaporating basin, and in this way the finer light material may be eliminated and the heavier fragments concentrated at the bottom of the dish. As it is often necessary to treat several pounds of rock before an adequate " heavy " residue is obtained, repeated panning is resorted to, using more than one dish at first, but gradually reducing the quantity of material until it can all be concentrated in one receptacle. Thus obtained, the concentrate is dried in the usual way and then submitted to a bromoform separation to isolate the " heavier " constituents. If the authigenous material is such as to mask the character of the fragments, clarification by means of dilute acid may be carried out as previously described.

3. *Microscopical Examination of Detrital Sediments.* A systematic investigation of the detrital grains of a given sample is strongly recommended, until by experience one has become proficient in the art of recognising and discriminating between associated mineral species. The plan of procedure may be summarised as follows :—

1. *With transmitted white light, low and high power objectives.*
   - (*a*) Colour. Transparency, translucency or opacity.
   - (*b*) Habit. Presence or absence of crystal faces.
   - (*c*) Shape. Regular or irregular.
   - (*d*) Size. Estimate or measure, if necessary, with eyepiece micrometer.
   - (*e*) Fracture. Uneven, conchoidal, etc.
   - (*f*) Parting. Linear or irregular.
   - (*g*) Cleavage. Principal and subordinate directions.
   - (*h*) Abrasion, Degree of. Angularity, subangularity, roundness.

(*i*) Refractive Index. Compare with Canada balsam (1.55).

2. *With reflected light against dark background to slide.*
   (*a*) Lustre. Adamantine, metallic, submetallic, vitreous, resinous, etc.
3. *With transmitted light, polariser inserted.*
   (*a*) Pleochroism. Presence or absence.
   Weak or strong.
   Colour change with orientation of grain.
4. *With transmitted light, crossed nicols.*
   (*a*) Isotropism or anisotropism.
   (*b*) Birefringence. High, medium or low.
   (*c*) Extinction. Straight or oblique.
5. *With convergent light, high power objective, crossed nicols and Bertrand lens.*
   (*a*) Detection of interference figure: Uniaxial or biaxial.
   (*b*) Determination of the sign of the crystal by means of a quartz wedge.

[N.B.—The interference figure may often be better observed in sand grains by taking out the eyepiece and dispensing with the Bertrand lens.]

Since the chief diagnostic evidence for a given mineral frequently depends on a critical examination of its optical properties, it may be of use to summarise such properties as follows:—

SUMMARY OF THE OPTICAL PROPERTIES OF DETRITAL MINERALS.

1. *Amorphous* (*Non-crystalline*). Shapeless grains. No variation in directional properties. *Examples*:—Glauconite, Limonite.
2. *Cubic System.* Grains are singly refracting, isotropic and never pleochroic. *Examples*:—Fluor, Garnet, Diamond and Spinel. Under conditions of internal strain, some species may be anisotropic, *e.g.*, Garnet, Fluor.
3. *Hexagonal System.* Grains are doubly refracting and sometimes pleochroic if coloured. Basal grains or those abraded transverse to the hexad-axis are isotropic, and yield uniaxial interference

figures. Prismatic grains give straight extinction. *Examples* :—Apatite and Corundum.

4. *Rhombohedral System.* Grains are doubly refracting, and frequently pleochroic if coloured. Basal grains or those abraded at right angles to the principal axis are isotropic and yield uniaxial interference figures. Prismatic grains show straight extinction. *Examples* :—Calcite and Tourmaline.
5. *Tetragonal System.* Grains are doubly refracting and sometimes pleochroic if coloured. Basal grains or those abraded transverse to the principal axis are isotropic and yield uniaxial interference figures. Straight extinction for prismatic grains. *Examples* :—Anatase, Cassiterite, Rutile, Xenotime and Zircon.
6. *Orthorhombic System.* Grains are doubly refracting and often pleochroic if coloured. Never isotropic. Biaxial interference figure. All grains show straight extinction. *Examples* :—Andalusite, Brookite, Enstatite and Topaz.
7. *Monoclinic System.* Grains are doubly refracting, often pleochroic when coloured. Never isotropic. Biaxial interference figure. Straight or oblique extinction according to crystal plane to which surfaces examined are parallel. *Examples* :—Gypsum, Orthoclase, Epidote and Sphene.
8. *Triclinic System.* Grains are doubly refracting and usually pleochroic if coloured. Never isotropic. Biaxial interference figure. Grains usually give oblique extinction. *Examples* :—Kyanite and Plagioclase Felspar.

[N.B.—Exceptionally for grains of biaxial minerals, the major portion of the upper and lower surfaces searched by the microscope may be parallel to the circular section of the indicatrix. Such grains will not show birefringence.]

CHAPTER II.

THE CRYSTALLOGRAPHICAL, PHYSICAL AND OPTICAL PROPERTIES OF THE PRINCIPAL DETRITAL MINERALS.

In the following pages will be found a summary of the principal properties of detrital minerals likely to be met with in sediments. The information given should be sufficient in itself in most cases for determining a particular species, but a working knowledge of crystallography is assumed throughout.

The crystallographic properties (system, habit and structure) refer to well crystallised species of the particular mineral under discussion, modifications in habit and structure of detrital grains being noted in the paragraph "Characters in Sediments."

The physical properties include cleavage, fracture, parting, hardness, specific gravity, lustre and colour, and serve both for primary minerals and their detrital modifications, as is the case with the optical properties given. The refractive indices are quoted in all instances for yellow light, and the values given for 2E or 2V are also for yellow light. Electromagnetic and electrostatic properties are further noted as an aid to mechanical processes of separation.

The paragraphs dealing with the characters of detrital grains embody particulars of their normal appearance under the microscope, and represent the average results of examination of a very large and varied selection of grains from stratigraphical horizons, both in this country and from various parts of the world. The indication in each case of possible sources of derivation of grains is

by no means exhaustive, but is included to help in instances where definite parent rocks are sought in tracing the direction of transport of material, and for general palæogeographical investigations.

Under "Remarks" will be found hints in cases where confusion between species may arise, and notes relevant to the particular mineral concerned.

ANATASE (Octahedrite). [Fig. 2

Chem. Comp. TiO_2. Oxide of Titanium.
System. Tetragonal.
Habit. Bipyramidal, acute or obtuse, often tabular.
Structure. Crystalline, rarely massive.
Cleavage. Perfect parallel to (001) and (111).
Fracture. Subconchoidal, uneven.
Hardness. 5.5 to 6.
Spec. Grav. 3.82 to 3.95.
Lustre. Adamantine, submetallic.
Colour. Yellow, brown, indigo-blue, black. Transparent to opaque.
Mag. Prop. Non-magnetic.
Elect. Prop. Moderately good conductor.
Opt. Prop. R.I. very high, $\omega = 2.5618$, $\epsilon = 2.4886$.
Birefringence high, $\omega - \epsilon = 0.0732$. Optically uniaxial, negative.
Non-pleochroic. Basal sections isotropic.
Characters in Sediments. Grains usually well rounded, frequently tabular with modified edges. They show a tendency to basal development due to (001) cleavage: such grains exhibit good interference figure. Parallel intergrowth of tabular crystals common. Pyramidal forms also found showing striations parallel to intersection with prism face $\{110\}$. Less commonly angular cleavage fragments or irregularly fractured grains occur. Both primary and secondary grains are found, often in the same sample: the latter are derived *in situ* from the decomposition of titaniferous minerals such as ilmenite, and usually show marked angularity; the former are detrital, as evidenced by the degree of rounding which results from prolonged abrasion.
Possible Sources of Derivation. Crystalline metamorphic rocks, or of secondary origin as above.

FIG. 2. ANATASE.

1, 3. Pliocene Sands, St. Keverne, Cornwall. [x 120.]
2, 6. As for 1 & 3. [x 70.]
4, 5. Tunbridge Wells Sand, Tunbridge Wells, Kent. [x 70.]
7-9. Alluvials, Minas Geraes, Brazil. [x 6.]

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ANDALUSITE. [Fig. 3

Chem. Comp. $Al_2O_3.SiO_2$. Fe and Mn may be present.
System. Orthorhombic.
Habit. Prismatic, rarely euhedral.
Structure. Usually crystalline.
Cleavage. Distinct parallel to (110), imperfect parallel to (100), more rarely parallel to (010).
Fracture. Uneven and irregular.
Hardness. 7.5.
Spec. Grav. 3.16 to 3.20.
Lustre. Vitreous.
Colour. Colourless, white, and pale shades of red, green, brown and violet. Transparent to translucent.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. high, $\alpha = 1.632$, $\beta = 1.638$, $\gamma = 1.643$.
Birefringence low, $\gamma - \alpha = 0.011$. Optically biaxial, negative.
Optic axial plane parallel to (010). *Bxa* normal to (001).
Pleochroism intense in some varieties, blood-red to colourless.
Straight extinction parallel to prism edge.
Characters in Sediments. Grains very variable in form; commonly irregular and subangular, but rounded prismatic types also met with. Frequently show presence of inclusions of graphite or carbonaceous matter,† also alteration products such as muscovite or kaolin, all causing a turbid appearance of the mineral. These features serve to differentiate andalusite from topaz (with which it may sometimes be confused), but the pleochroism of the former, when present, is an infallible guide. This pleochroism is best seen in prismatic grains orientated in an east-west position.
Possible Sources of Derivation. Granitic and metamorphic rocks.

Remarks.—At one time detrital andalusite was thought to be restricted to Tertiary deposits, but Mr. G. MacDonald Davies has shown conclusively that it occurs as far back as in the Wealden sands near Oxford [29]. Dr. Gilligan has also recorded it from the Millstone Grit of Yorkshire [36].

† Chiastolite.

APATITE.

Chem. Comp. Fluor-Apatite, $Ca_4(CaF)(PO_4)_3$. Chlor-Apatite, $Ca_4(CaCl)(PO_4)_3$.
Intermediate compounds occur with both F and Cl. Also traces of Mn, Di, Ce and Hydroxyl.
System. Hexagonal.
Habit. Prismatic, bipyramidal, or with basal pinacoid.
Structure. Usually crystalline, sometimes acicular, massive, granular or compact.
Cleavage. Imperfect parallel to (0001); more rarely parallel to $(10\bar{1}0)$.
Fracture. Uneven, conchoidal.
Hardness. 5. Less in massive varieties (4.5).
Spec. Grav. 3.17 to 3.23.
Lustre. Vitreous to sub-resinous.
Colour. Commonly white, colourless or shades of green. Transparent.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. high, $\omega = 1.6335$, $\epsilon = 1.6316$.
Birefringence very low, $\omega - \epsilon = 0.0019$. Optically uniaxial, negative.
Some coloured varieties weakly pleochroic. Straight extinction.
Basal sections isotropic.
Characters in Sediments. Rounded elongated prismatic grains most common, sometimes with minute indeterminable inclusions arranged parallel to the principal axis: these may be fluid. Grains frequently very small, often showing evidence of solution.
Possible Sources of Derivation. Igneous rocks, especially granites and syenites.

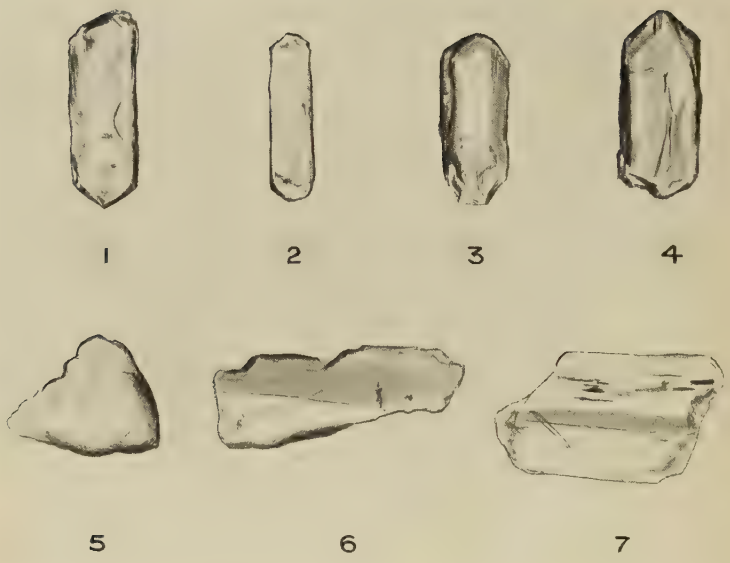

FIG. 3. ANDALUSITE.

1-4. Pliocene Sands, Cornwall.
5. Blown Sands, Newgale, Pembrokeshire.
6, 7. Pliocene Sands, Cornwall. [All x 60.]

FIG. 4. AUGITE.

1, 2. Recent Sands, Rosslare, Co. Wexford.
3. Recent Sands, Cape Verde Is.
4. Blown Sands, Newgale, Pembrokeshire. [All x 70.]

To face page 33.

AUGITE (Monoclinic Pyroxene). [Fig. 4

Chem. Comp. Silicate of lime, magnesium, iron and aluminium, etc.

System. Monoclinic.

Habit. Commonly prismatic, with varying terminations.

Structure. Usually crystalline, sometimes granular.

Cleavage. Good parallel to (110), more rarely parallel to (100).

(001) parting frequently observed, evidenced by twin lamellæ.

Fracture. Uneven.

Hardness. 5 to 6.

Spec. Grav. 3.2 to 3.6 (varies with composition).

Lustre. Vitreous, sometimes resinous.

Colour. Shades of green to blackish-green. Sometimes brown.

Mag. Prop. Moderately magnetic; varies with the amount of iron present.

Elect. Prop. Moderately good conductor.

Opt. Prop. R.I. very high, $\alpha = 1.712$, $\beta = 1.717$, $\gamma = 1.733$.

Birefringence high, $\gamma - \alpha = 0.021$. Optically biaxial, positive.

Optic axial plane parallel to (010). *Bxa* inclined at 38° to c axis. $2V = 61°$†.

Slightly pleochroic in some titaniferous varieties.

Characters in Sediments. Grains usually either rounded prismatic forms or irregular cleavage fragments, the latter often showing the emergence of an optic axis. Fractured or " broken " grains are sometimes met with which are very characteristic of the particular horizon at which they occur. Other varieties of pyroxene are comparatively rare as detrital grains, though pale green diopside may sometimes occur.

Possible Sources of Derivation. Intermediate and basic igneous rocks.

† Varies with the amount of Al_2O_3 and Fe_2O_3 present.

BARYTES.

Chem. Comp. $BaSO_4$.
System. Orthorhombic.
Habit. Prismatic, with basal plane strongly developed.
Structure. Crystalline, massive or lamellar.
Cleavage. Perfect parallel to (001) and (110).
Fracture. Uneven.
Hardness. 2.5 to 3.5.
Spec. Grav. 4.5.
Lustre. Vitreous, pearly.
Colour. Colourless, bluish-white or yellow. Transparent to translucent.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. high, $\alpha = 1.636$, $\beta = 1.637$, $\gamma = 1.647$.
Birefringence low, $\gamma - \alpha = 0.011$. Optically biaxial, positive.
Optic axial plane parallel to (010). *Bxa* normal to (100). Prismatic grains give straight extinction.
Diamond-shaped cleavage grains may show emergence of the *bxo*.
Characters in Sediments. Fragments of this mineral are varied in character; frequently diamond-shaped basal forms occur, also irregular prismatic flakes. Sharply angular cleavage fragments are common; but these do not yield good interference figure. Grains rarely show signs of wear, though they may be intensely fractured.
Possible Sources of Derivation. From sandstones, in which it acts as the cementing medium; from veins in limestones associated with calcite; from the gangue of metalliferous veins or from massive deposits of barytes associated with calcareous sediments.

Remarks.—Rarely met with as detrital grains; presence in residue usually due to the disintegration of the cementing medium of a sand on treatment of the latter for "heavy" mineral analysis. Celestite is the same in this respect, though of much rarer occurrence than barytes.†

† Thomas, H. H., Q.J.G.S., vol. lxv., 1909, p. 234.

BIOTITE (Black Mica).

Chem. Comp. Silicate of aluminium, magnesium, iron and potassium.

System. Monoclinic.

Habit. Tabular; short prismatic crystals with well-developed basal planes.
Frequently twinned.

Structure. Irregular, but strongly laminated. Crystals rare.

Cleavage. Perfect basal (001).

Fracture. Uneven.

Hardness. 2.5 to 3.

Spec. Grav. 2.95 to 3.

Lustre. Vitreous, resinous or dull.

Colour. Dark green, brown to blackish-brown.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. low, $\alpha = 1.504$, $\beta = 1.589$, $\gamma = 1.589$.
Birefringence high, $\gamma - \alpha = 0.0850$. Optically biaxial, negative.
Bxa normal to (001), but optic axial angle small in certain varieties, giving pseudo-uniaxial interference figure.
Pleochroism varies with composition, being strongest in the deep brown facies (phlogopite): brown to dull yellow or colourless.

Characters in Sediments. Occurs mostly as brown coloured cleavage flakes with jagged edges; seldom worn. Pleochroic haloes round crystals of zircon, xenotime, allanite, etc., enclosed in the mica are of frequent occurrence, especially in the deep-brown varieties. Detrital flakes tend to lie with (001) in the plane of the slide, and hence are non-pleochroic. Partial alteration to chloritic matter, producing a "bleached" grain, is commonly observed.

Possible Sources of Derivation. Igneous and metamorphic rocks.

BROOKITE. [Fig. 5

Chem. Comp. TiO_2.
System. Orthorhombic.
Habit. Prismatic, tabular or pyramidal.
Structure. Crystalline.
Cleavage. Poor parallel to (110).
Fracture. Subconchoidal, irregular.
Hardness. 5.5 to 6.
Spec. Grav. 3.87 to 4.084.
Lustre. Resinous, vitreous, submetallic.
Colour. Shades of brown and yellow. Translucent.
Mag. Prop. Non-magnetic.
Elect. Prop. Moderate conductor.
Opt. Prop. R.I. very high, $\alpha = 2.5832$, $\beta = 2.5856$, $\gamma = 2.7414$. Birefringence very high, $\gamma - \alpha = 0.1582$. Optically biaxial, positive.

Platy forms (100) give characteristic interference figure; *bxa* normal to (100); optic axial angle small. Optic axial plane is parallel to (001) for red and yellow light, and parallel to (010) for blue and green light; the effect of this is to produce a pseudo-uniaxial figure for greenish-yellow light, which is a property aiding the identification of the mineral and its distinction from rutile.

Characters in Sediments. Grains usually subangular and irregular, sometimes occurring as tabular flakes of a distinctive yellowish-brown colour. Grains flattened parallel to (100) may show striations parallel to the principal axis. Occasionally weakly pleochroic grains are met with. Very pale coloured varieties frequently show signs of much abrasion.

Possible Sources of Derivation. Acid igneous and crystalline metamorphic rocks; may also be derived *in situ* from the decomposition of a titanium-bearing mineral.

Remarks.—On the whole a rare mineral in sands. Usually associated with either anatase or rutile, or both.

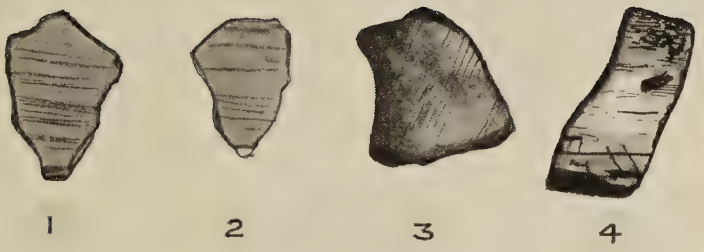

FIG. 5. BROOKITE.

1, 2. Alluvials, Minas Geraes, Brazil. [x 5.]
3. Pliocene Sands, St. Erth, Cornwall. [x 120.]
4. Alluvials, West Africa. [x 30.]

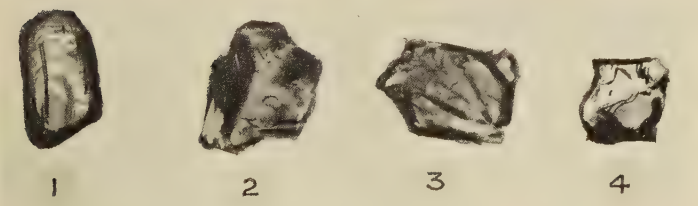

FIG. 6. CASSITERITE.

1. Alluvials, Nigeria.
2-4. Alluvials, Malay States. [All x 70.]

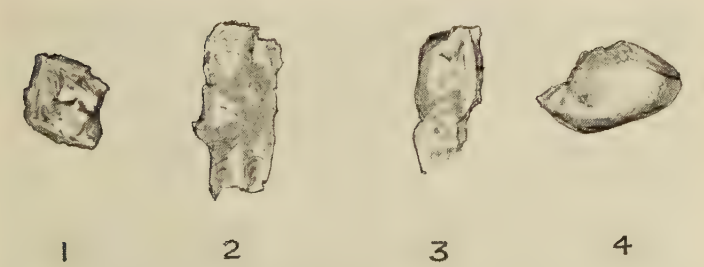

FIG. 7. EPIDOTE.

1-4. Alluvials, W. Africa. [All x 70.]

To face page 36.

CALCITE.

Chem. Comp. $CaCO_3$.

System. Rhombohedral.

Habit. Highly varied and frequently complex. Commonly prismatic, rhombohedral, scalenohedral or twinned.

Structure. Crystalline or massive.

Cleavage. Perfect parallel to unit rhombohedron ($10\bar{1}1$).
Good parting parallel to ($01\bar{1}2$) in twin crystals, more rarely parallel to ($11\bar{2}0$).

Fracture. Irregular, but rare.

Hardness. Varies with composition, but usually about 3.

Spec. Grav. 2.713 to 2.723.

Lustre. Vitreous, pearly.

Colour. Colourless, white or pale shades of yellow, red or brown due to impurity.
Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. low for ϵ, high for ω. $\omega = 1.65849$, $\epsilon = 1.48625$.
Birefringence very high, $\omega - \epsilon = 0.17224$. Optically uniaxial, negative.
($10\bar{1}1$) cleavage plates show partial interference figure.

Characters in Sediments. Usually occurs as rhombohedral grains, slightly rounded. Twin striæ parallel to the major diagonals of the cleavage flakes ($10\bar{1}1$) commonly observed.

Possible Sources of Derivation. Chiefly from sedimentary rock masses, either as a primary or secondary constituent. Also from decomposition of lime-silicate minerals in igneous rocks. Recrystallised from shell-fragments.†

Remarks.—Calcite can conveniently be separated from the " light " material of a sample by using bromoform diluted with benzene to give a liquid of S.G. 2.7.

† Boswell, P. G. H., Geol. Mag., June, 1915, p. 255.

CASSITERITE (Tinstone). [Fig. 6

Chem. Comp. SnO_2.
System. Tetragonal.
Habit. Commonly euhedral. Bipyramidal, prismatic or twinned on (101).
Structure. Crystalline, massive, granular.
Cleavage. Imperfect parallel to (100), bad parallel to (111), trace parallel to (110).
Fracture. Subconchoidal, uneven.
Hardness. 6 to 7.
Spec. Grav. 6.8 to 7.1.
Lustre. Adamantine, submetallic or dull.
Colour. Brown, black, more rarely pale yellow or greyish-white. Translucent to opaque.
Mag. Prop. Non-magnetic.
Elect. Prop. Moderate conductor.
Opt. Prop. R.I. high, $\omega = 1.9966$, $\epsilon = 2.0934$.
Birefringence high, $\epsilon - \omega = 0.0968$. Optically uniaxial positive.
Birefringence colours frequently masked by natural colour.
Rarely pleochroic. Straight extinction of grain parallel to prism edge.
Characters in Sediments. Commonly occurs as dusky rounded prismatic grains, or as irregular rolled crystals. Well worn " knee-shaped " twins not uncommon in alluvials. Grains do not usually attain a large size. " Zoning " is a frequent feature.
Possible Sources of Derivation. From veins associated with granitic rocks. From metalliferous lodes.

CHALCEDONY (Flint).

Chem. Comp. SiO_2.
System. Doubtful.
Habit. Botryoidal, massive, compact.
Structure. Cryptocrystalline.
Cleavage. None.
Fracture. Conchoidal, irregular, splintery.
Hardness. 7.
Spec. Grav. 2.59 to 2.64.
Lustre. Resinous, dull.
Colour. Pale shades of blue, bluish-white, red; black or mottled.
Translucent to opaque.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. low, mean R.I. 1.537 (Canada balsam 1.55).
Birefringence low. Fibrous forms extinguish parallel to their length.
Characters in Sediments. Grains either sharply angular or rounded. With polarised light little change is noted, homogeneity of colour and appearance being due to the cryptocrystalline structure. Small and almost opaque fracture " chips " are common in the lighter portion of many of the older Tertiary deposits of England.

Remarks. — It is convenient to notice here the Chert grains which frequently occur as constituents of detrital sediments; such grains often preserve traces of organic structure, or they may be associated with pellets of pyrites.

CHLORITE.

Chem. Comp. Ill-defined family of micaceous minerals frequently representing alteration products of amphiboles and micas. Essentially silicates of aluminium, ferrous iron, magnesium and hydroxyl, the two chief crystalline varieties being Penninite and Clinochlore.

System. Monoclinic (pseudo-rhombohedral symmetry in Penninite).

Habit. Pseudo-hexagonal plates with bevelled edges; tabular, with prominent basal plane.

Structure. Foliated, massive. Rarely crystalline.

Cleavage. Perfect basal; cleavage flakes flexible.

Fracture. Irregular.

Hardness. 2 to 2.5.

Spec. Grav. 2.65 to 3. (Varies with composition.)

Lustre. Vitreous, (001) pearly.

Colour. Shades of green, more rarely pale greenish-yellow. Transparent to translucent.

Mag. Prop. Weakly magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. low, $\alpha = 1.585$, $\beta = 1.588$, $\gamma = 1.596$ (Clinochlore).

Birefringence low, $\gamma - \alpha = 0.011$. Different varieties may show biaxial interference figures, and may be either positive or negative, while the great variation in the optic axial angle occasions the pseudo-uniaxial appearance of Penninite, where 2V may be 0°.

Pleochroism noticed in some varieties, especially those of deep colour: dark green to yellowish-green.

Characters in Sediments. Cleavage flakes common, general appearance somewhat resembling mica. Grains frequently exhibit interference figures which materially aid identification of the group, though specific determination in some cases is a matter of great difficulty, if not of impossibility, in detrital grains.

Possible Sources of Derivation. From slates, phyllites and similar metamorphic rocks.

Remarks.—The so-called "chlorite" derived from relaxed basic igneous rocks (more particularly their ferro-magnesian constituents), is poorly individualised as crystal and certainly rare as either penninite or clinochlore. In such cases it is better designated as "chloritic matter" implying considerable variation in composition according to precise nature of parent species and destabilising environment.

CHROMITE.

Chem. Comp. $FeO.Cr_2O_3$.
System. Cubic.
Habit. Octahedral or combination of octahedron and dodecahedron.
Structure. Rarely crystalline, commonly massive.
Cleavage. None.
Fracture. Uneven.
Hardness. 5.5.
Spec. Grav. 4.32 to 4.57.
Lustre. Metallic to submetallic, rarely dull.
Colour. Black or brownish-black, frequently with purple tarnish.
Mag. Prop. Moderately magnetic.
Elect. Prop. Good conductor.
Opt. Prop. Opaque in transmitted light, except in very thin section, when the deep brown colour and isotropic character are apparent.
Characters in Sediments. Occurs as rounded octahedral grains or as subangular and irregular fragments. Deposits derived from ultrabasic rocks often contain a high percentage of this mineral, which is identified chiefly by its submetallic lustre in reflected light, and by its colour and form.
Possible Sources of Derivation. Chiefly from peridotites, serpentines and associated ultrabasic rocks; more rarely from crystalline schists.

Remarks.—The microscopical determination of chromite is not always convincing, and, if possible, should be supplemented by chemical test. (With borax bead, chromium yields green colour in both oxidising and reducing flames.)

Mr. G. M. Davies has described detrital chromite from the Beer Stone (Middle Chalk) of Beer Head, S.E. Devon. See Geol. Mag., 1919, p. 506.

COLUMBITE AND TANTALITE.

Chem. Comp. $(Fe,Mn)Nb_2O_6$ (Columbite molecule), $(Fe,Mn)Ta_2O_6$ (Tantalite molecule), with intermediate compounds.

Sytem. Orthorhombic.

Habit. Stumpy prismatic crystals commonly with basal plane, pyramid and dome terminations. Sometimes highly complex forms occur.

Structure. Crystalline, more rarely massive.

Cleavage. Good parallel to (100), imperfect parallel to (010).

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 5.3 (Columbite), 7.3 (Tantalite); varies with composition.

Lustre. Submetallic, resinous (Columbite).

Colour. Black, blackish-grey, sometimes iridescent. Columbite sometimes translucent.

Mag. Prop. Weakly magnetic.

Elect. Prop. Good conductors.

Opt. Prop. Opaque.

Characters in Sediments. Grains of these minerals occur frequently in sands and gravels associated with cassiterite, monazite, beryl and rarer species; they are usually well rounded, but are difficult to identify microscopically. Columbite may exhibit a dark brownish-grey translucency in very thin grains, but this character cannot always be relied upon; tantalite is essentially opaque. If the presence of these minerals is suspected, confirmation should be obtained by chemical means.

Possible Sources of Derivation. Primarily in pegmatite veins associated with acid igneous rocks.

Remarks.—Neither of these minerals has yet been recorded from the sediments of the British Isles, the chief localities being in Australia, Greenland, Siberia and Bavaria.

For chemical test, fuse with borax, dissolve in HCl, and boil solution with tin; a blue colour indicates the presence of niobium. Tantalite gives a bluish-green bead with Na_2CO_3 in the oxidising flame.

CORDIERITE.

Chem. Comp. $4(MgFe)O.4(Al_2O_3).10SiO_2.H_2O$.
System. Orthorhombic.
Habit. Euhedral prismatic crystals; often twinned; sometimes complex.
Structure. Crystalline, granular.
Cleavage. Good parallel to (010), poor parallel to (100) and (001).
Fracture. Subconchoidal.
Hardness. 7 to 7.5.
Spec. Grav. 2.60 to 2.66.
Lustre. Vitreous.
Colour. Shades of blue or yellowish-grey.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. low, $\alpha = 1.532$, $\beta = 1.536$, $\gamma = 1.539$. Birefringence low, $\gamma - \alpha = 0.007$. Optically biaxial, negative. Optic axial plane parallel to (100). *Bxa* normal to (001). Optic axial angle variable, $2V = 40°$ to $84°$. Usually faintly pleochroic. Straight extinction parallel to prism edge.
Characters in Sediments. Generally occurs as small subangular grains, almost colourless, weakly pleochroic and birefringent. Minute and opaque inclusions are not uncommon; these may be surrounded by pleochroic haloes. In its unaltered form it is of rare occurrence in sediments, Pinite being the usual product met with. Pinite is recognised by its green or greenish-brown colour, micaceous habit and its tendency to form cryptocrystalline aggregates.
Possible Sources of Derivation. Crystalline schists and gneisses, less commonly from acid igneous rocks.

Remarks.—Cordierite being of low specific gravity will occur in the light concentrate, and may thus be easily confused with quartz, or overlooked altogether. It is distinguished from the latter by its biaxial interference figure, and by its pleochroism if developed.

CORUNDUM.

Chem. Comp. Al_2O_3.
System. Rhombohedral.
Habit. Hexagonal bipyramidal. Rounded crystals.
Structure. Granular.
Cleavage. Parallel to (0001), but rarely seen in small grains.
Both basal and rhombohedral partings occur.
Fracture. Conchoidal, uneven.
Hardness. 9.
Spec. Grav. 3.95 to 4.10.
Lustre. Adamantine, vitreous.
Colour. Frequently colourless, or shades of blue (Sapphire), red (Ruby), or yellowish-brown.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. high, $\epsilon = 1.7598$, $\omega = 1.7690$.
Birefringence low, $\omega - \epsilon = 0.0092$. Optically uniaxial, negative.
Strongly coloured varieties are pleochroic, particularly sapphire : blue to bluish-green.
Characters in Sediments. Usually well rounded grains of irregular outline. Less commonly as basal plates determined by parting and fracture, yielding good uniaxial figure. The colour is often unevenly distributed in the grains, some appearing very "blotchy." Anomalous optical properties are sometimes noted which are probably due to twinning, *e.g.*, pseudo-biaxial figure.
Possible Sources of Derivation. Igneous or metamorphic rocks, especially contact-metamorphosed limestones. Alluvial deposits.

Remarks.—The combination of a high R.I. and low birefringence is a useful aid to identification.

DIAMOND.

Chem. Comp. Pure carbon.
System. Cubic.
Habit. Octahedral, curved hexakis-octahedral, sometimes twinned.
Structure. Crystalline.
Cleavage. Perfect parallel to (111).
Fracture. Conchoidal.
Hardness. 10.
Spec. Grav. 3.5.
Lustre. Brilliant, adamantine, sometimes resinous in places.
Colour. Colourless, yellow, red or black. Transparent to translucent.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. extremely high, 2.42. Optically isotropic.
Characters in Sediments. Small rounded and much faceted grains of a yellowish-white colour, are sometimes found, especially in alluvial deposits, when they are frequently associated with other rare minerals. The very high R.I. and isotropic character serve to differentiate diamond from zircon, with which it is sometimes confused in detrital sediments.
Possible Sources of Derivation. Peridotite and associated ultrabasic rocks; alluvial sands and gravels.

Remarks. — An extremely rare mineral in sediments, only occurring locally under specific conditions.

EPIDOTE. [Fig. 7

Chem. Comp. $Ca_2(Al.OH)(Al,Fe)_2(SiO_4)_3$. Fe may replace both Al and Ca.

System. Monoclinic.

Habit. Prismatic with dissimilar terminations. Often striated parallel to prism zone.

Frequently twinned about (100), rarely parallel to (001).

Structure. Crystalline, fibrous, massive.

Cleavage. Perfect basal, parallel to (001). Imperfect parallel to (100).

Fracture. Uneven.

Hardness. 6 to 7.

Spec. Grav. 3.25.

Lustre. Vitreous, sometimes resinous.

Colour. Greenish-yellow, dark green, shades of brown.

Mag. Prop. Weakly magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. very high, $\alpha = 1.7238$, $\beta = 1.7291$, $\gamma = 1.7343$.

Birefringence high, $\gamma - \alpha = 0.0144$. Optically biaxial, negative.

Optic axial plane parallel to (010), normal to principal cleavage. *Bxa* inclined at 22°37′ to normal of (001). $2V = 92°$ (varies with amount of Fe_2O_3 present). Pleochroism weak: greenish-yellow to colourless, noticeable in thick grains.

Characters in Sediments. Irregular and rather angular grains common, the flattened " platy " forms often exhibiting partial (compass-needle) interference figure, due to emergence of one optic axis. Pale yellowish-green subangular grains are very characteristic of certain sands, and are remarkable for their transparency.

Possible Sources of Derivation. Crystalline metamorphic rocks, especially altered impure limestones. Also from highly altered igneous rocks originally rich in ferromagnesian minerals.

Remarks.—In certain local environments, involving crystalline schists, amphibolites, etc., detrital Zoisite (the orthorhombic member of the Epidote group) may be met with. Zoisite is similar to epidote (as above described) in composition and general physical properties, but differs from that mineral in being optically positive, and having a lower R.I., and birefringence. Grains are usually of a greyish-white colour.

FLUOR.

Chem. Comp. CaF_2.
System. Cubic.
Habit. Either simple or modified cube; interpenetrant twins common.
Structure. Crystalline, compact, massive.
Cleavage. Perfect parallel to (111).
Fracture. Conchoidal.
Hardness. 4.
Spec. Grav. 3.18 to 3.189.
Lustre. Vitreous.
Colour. Commonly white, green, blue or purple; also pink, brown and intermediate shades. Transparent to translucent.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. very low. 1.4336. Optically isotropic.
Characters in Sediments. Frequently occurs as octahedral cleavage fragments, subangular or irregular. Rounded grains rare. Triangular plates with modified edges sometimes found. Detrital grains of this mineral are often violet in colour, though the colouring matter may not permeate the whole grain, thus rendering it "blotchy."
Possible Sources of Derivation. Acid igneous rocks, metamorphic rocks and metalliferous veins. Also limestones.

GARNET. [Fig. 8

Chem. Comp. Group of orthosilicates with general formula $R''_3R'''_2(SiO_4)_3$.
R″ may be Ca, Mg, Fe″ or Mn. R‴ may be Al, Fe‴ or Cr.
Species: *Grossularite* (Ca), *Pyrope* (Mg), *Almandine* (Fe), *Spessartite* (Mn), *Andradite* (CaFe), *Uvarovite* (Cr).

System. Cubic.

Habit. Dodecahedral, trapezohedral or combination of both forms.

Structure. Crystalline, massive.

Cleavage. Imperfect dodecahedral, parallel to (110).

Fracture. Irregular, subconchoidal.

Hardness. 7.

Spec. Grav. 3.8, but varies considerably with composition.

Lustre. Vitreous, resinous.

Colour. Varies with species. *Grossularite,* white, greenish-yellow, brown or pale red. *Pyrope,* deep red to black. *Almandine,* deep brownish-red to ruby red. *Spessartite,* brown. *Andradite,* yellow, brown, green, black. *Uvarovite,* emerald green.

Mag. Prop. Moderately magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. high, 1.7. Optically isotropic, though some crystals exhibit anomalous interference colours due to strain.

Characters in Sediments. Detrital garnets are commonly irregular, often fractured, seldom well rounded. Pale pink grains (derived from Almandine) are the most prevalent. Grains frequently void of recognisable crystal faces. Platy forms, determined by (110) cleavage, showing subconchoidal fracture or marked re-entrant angles are sometimes met with. Inclusions common in many instances.

Possible Sources of Derivation. Igneous and metamorphic rocks, particularly crystalline gneisses and schists. Alluvial deposits.

Remarks.—Garnet varies widely in character in detrital sediments, specific physical features often typifying grains from definite horizons; on this account it is of great importance for correlation purposes, and also for suggesting the conditions under which deposition took place. See particularly Bosworth [17].

FIG. 8. GARNET.

1. Permian Sandstone, Tynemouth, Northumberland. [x 30.]
2. Tertiary Sandstone, Angola. [x 30.]
3. (a) Recent Sand, Ceylon. [x 70.]
   (b) Alluvials, Ceylon. [x 20.]
   (c) Recent Sand, Brazil. [x 20.]
   (d) Pliocene Sand, St. Erth, Cornwall. [x 30.]

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GLAUCONITE. [Fig. 10

Chem. Comp. Silicate of K, Fe, Al with H_2O.
System. Non-crystalline.
Structure. Amorphous. Earthy aggregates, granular, fibrous or as irregular grains. Some varieties show good lamellar structure.
Hardness. 2.
Spec. Grav. 2.2 to 2.84.
Lustre. Dull, sometimes vitreous.
Colour. Various shades of green, olive, blackish-yellow. Brown when altered.
Mag. Prop. Moderately magnetic.
Elect. Prop. Poor conductor.
Opt. Prop. R.I. low when compared with quartz. Birefringence variable, but aggregates commonly present low polarisation tints. Optically biaxial in lamellar aggregates. Some varieties decidedly pleochroic: green to yellowish-green; seen to advantage in lamellar types.
Characters in Sediments. Rounded or irregular grains or aggregates, usually characteristic of the "light" material of certain sediments. Frequently occurs as glauconitic casts of foraminifera. Commonly dark green in colour, if not altogether opaque; strong tendency to show decomposition to limonite.
Possible Sources of Derivation. Sedimentary rocks, more rarely from amygdaloidal lavas. Frequently of organic origin.

Remarks. — Glauconite is a mineral at present imperfectly understood. It occurs in abundance at certain stratigraphical horizons, especially in the Cretaceous Greensands. Its properties undoubtedly vary largely with the amount of iron present, this factor affecting the S.G., which in some cases is >2.83. Most varieties are decomposed by HCl, hence in preliminary treatment of samples with this acid much of the glauconite may be lost. Its prolific occurrence in the Greensands would seem to be a function of its chemical stability in this instance, rather than of accentuated development at that epoch. There is no reason to suppose that it was initially less common in older than in younger sediments; on the contrary, its characters frequently suggest derivation and redeposition from pre-existing deposits, particularly in some of the Jurassic sands. See Boswell [8].

GLAUCOPHANE. [Fig. 9

Chem. Comp. $NaAl(SiO_3)_2.(Fe.Mg)SiO_3$.
System. Monoclinic.
Habit. Prismatic, short " stumpy " crystals.
Structure. Crystalline.
Cleavage. Good parallel to (110).
Fracture. Uneven.
Hardness. 5 to 6.
Spec. Grav. 2.991.
Lustre. Vitreous, pearly on cleavage fragments.
Colour. Blue to bluish-black.
Mag. Prop. Moderately magnetic.
Elect. Prop. Moderate conductor.
Opt. Prop. R.I. high, $\alpha = 1.6212$, $\beta = 1.6381$, $\gamma = 1.6390$.
Birefringence high, $\gamma - \alpha = 0.0178$. Optically biaxial, negative.
Optic axial plane parallel to (010). Oblique extinction, 3° to 11°. Pleochroism marked : blue to lavender-blue or violet.
Characters in Sediments. Commonly occurring as rounded or irregular prismatic grains of decided purplish-blue colour and with distinctive pleochroism. Abraded cleavage plates (110) also found.
Possible Sources of Derivation. Metamorphic rocks, especially schistose types. Eclogites. Crystalline limestones.

FIG. 9. GLAUCOPHANE AND HORNBLENDE.

1, 3. Glaucophane from Miocene Sands, Trinidad. [x 70.]
2, 4. Hornblende from Miocene Sands, Trinidad. [x 70.]
5. Glaucophane from Blown Sands, Newgale, Pembrokeshire. [x 70.]
6. Glaucophane from Glacial Sands, Withybush, Haverfordwest, Pembrokeshire. [x 40.]
7. Hornblende from Blown Sands, Newgale, Pembrokeshire. [x 70.]

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GOLD. [Fig. 11

Chem. Comp. Native gold, sometimes alloyed with silver, iron or copper.
System. Cubic.
Habit. Octahedral, dodecahedral, more rarely cubic.
Structure. Rarely crystalline, usually in " platy " masses or as irregular aggregates.
Cleavage. None.
Fracture. Hackly. (Very ductile.)
Hardness. 2.5 to 3.
Spec. Grav. 12 to 20; varies according to amount of impurity present.
Lustre. Metallic.
Colour. Shades of yellow and yellowish-brown.
Mag. Prop. Non-magnetic.
Elect. Prop. Good conductor.
Opt. Prop. Opaque.
Characters in Sediments. Occurs as flattened, irregular grains with characteristic " pitted " surface. Rounded octahedra extremely rare.
Possible Sources of Derivation. Detrital sands and gravels; igneous rocks. Gold-quartz veins.

Remarks.—A mineral as yet unrecorded as a detrital species from British strata, but occurring locally in alluvial gravels, etc.

GYPSUM (Selenite).

Chem. Comp. $CaSO_4.2H_2O$.
System. Monoclinic.
Habit. Prismatic, flattened parallel to (010). Frequently twinned on (100), less commonly on (101).
Structure. Crystalline, fibrous, massive or granular.
Cleavage. Good parallel to (010), also parallel to (100).
Fracture. None. Glide planes may be developed parallel to ($\bar{1}03$) and ($\bar{5}09$).
Hardness. 1.5 to 2.
Spec. Grav. 2.314 to 2.328.
Lustre. Vitreous to dull; pearly on (010) faces.
Colour. Colourless, white, sometimes stained by impurity. Transparent to translucent.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. low, $\alpha = 1.5208$, $\beta = 1.5220$, $\gamma = 1.5305$. Birefringence low, $\gamma - \alpha = 0.0097$. Optically biaxial, positive.
Optic axial plane parallel to (010). *Bxa* inclined at $37\frac{1}{2}^\circ$ to normal of (100); optic axial angle (2E) large, 95°. (010) folia give extinction angles of 13° and 37°.
Characters in Sediments. Found as colourless, well formed crystal grains, somewhat rounded, or as " platy " cleavage fragments of a pseudo-rhombohedral character determined by (010) cleavage. Common constituent of marls and clays when it is often well crystallised. Frequently of secondary origin.
Possible Sources of Derivation. Sedimentary rocks, saline deposits, from volcanic regions, and metalliferous veins.

HÆMATITE.

Chem. Comp. Fe_2O_3.
System. Rhombohedral.
Habit. Euhedral; tabular parallel to (0001); platy.
Structure. Crystalline, laminated, massive or earthy.
Cleavage. Doubtful. Parting parallel to (0001) and ($10\bar{1}1$), due to lamellar twinning.
Fracture. Subconchoidal, irregular.
Hardness. 5.5 to 6.5.
Spec. Grav. 4.9 to 5.3.
Lustre. Brilliant, metallic. Earthy varieties red.
Colour. Steel grey. Translucent to opaque.
Mag. Prop. Moderately magnetic.
Elect. Prop. Good conductor.
Opt. Prop. Opaque in thick scales or grains. Translucent plates show high R.I., $\omega = 3.22$, $\epsilon = 2.94$, and high birefringence, $\omega - \epsilon = 0.28$, polarisation tint often masked by natural colour. Optically uniaxial, negative. Said to be pleochroic in sections perpendicular to basal plane: brownish-red to yellowish-red.†
Characters in Sediments. Commonly found as rounded earthy grains of a reddish-brown colour by reflected light, which is very characteristic. More rarely as rhombohedral grains (0001) or platy forms with splendent lustre.
Possible Sources of Derivation. Igneous and metamorphic rocks; metalliferous veins; limestones.

Remarks.—Hæmatite occurs in sediments both as a primary and secondary constituent. In the latter case its partial alteration to limonite may frequently be observed. A common "cementing" medium in sandstones.

† Iddings: Rock Minerals, 1906, p. 503.

HORNBLENDE. [Fig. 9

Chem. Comp. Complex silicate of Fe, Mg, Ca, Al and Na.
System. Monoclinic.
Habit. Prismatic.
Structure. Slender prismatic or acicular crystals. Fibrous (Actinolite), or compact.
Cleavage. Parallel to (110) usually well developed. Less distinct parallel to (100) and (010). Cleavage traces in cross sections (normal to prism zone) intersect at angle of 124°. Parting observed in twin crystals parallel to (100) and (010).
Fracture. Uneven, subconchoidal. Frequently occurs at right angles to prismatic cleavage.
Hardness. 5 to 6.
Spec. Grav. 3 to 3.3, varying with composition.
Lustre. Vitreous.
Colour. Dark green, brown, black. Translucent.
Mag. Prop. Moderately magnetic.
Elect. Prop. Moderate conductor.
Opt. Prop. R.I. high, $\alpha = 1.6398$, $\beta = 1.6431$, $\gamma = 1.6561$.
Birefringence low, $\gamma - \alpha = 0.0163$. Optically biaxial, negative.
Optic axial plane parallel to (010). *Bxa* inclined at low angle to normal of (100). Extinction angle approximately 15°.
Pleochroism marked, maximum absorption being in direction parallel to principal axis of crystal: dark brown or green to light brown or green respectively.
Characters in Sediments. Grains usually irregular or subangular, often of a bleached yellowish-green colour; slender prismatic cleavage fragments also common. The fibrous actinolitic types met with are frequently almost colourless and extinguish at angles varying from 8° to 12°. In some deposits both green and brown varieties of hornblende occur, the former usually being the more pleochroic.
Possible Sources of Derivation. Igneous and metamorphic rocks.

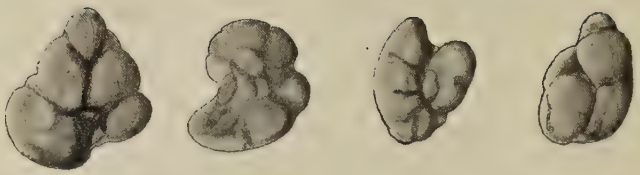

Fig. 10.

Fig. 11.

Fig. 12.

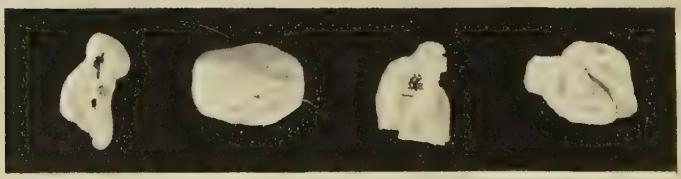

Fig. 13.

10. Glauconite Casts of Foraminifera). Upper Greensand, Chaldon Herring, Dorset. [× 50.]
11. Gold, Alluvials, W. Africa. [× 20.
12. Hypersthene, Santa Cruz. [× 30.
13. Ilmenite altered to Leucoxene, Upper Eocene, Auvers-sur-Oise, nr. Paris. [× 40.]

Figs. 10, 11, 13 by reflected light.

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HYPERSTHENE. [Fig. 12

Chem. Comp. $(Mg,Fe)SiO_3$.
System. Orthorhombic.
Habit. Prismatic, bipyramidal.
Structure. Crystalline.
Cleavage. Distinct parallel to (110), fair parallel to (100) and (010).
Fracture. Uneven.
Hardness. 5 to 6.
Spec. Grav. 3.4 to 3.5.
Lustre. Vitreous, pearly on cleavage faces.
Colour. Brownish-green, grey-green or olive. Translucent.
Mag. Prop. Weakly magnetic, varies with iron content.
Elect. Prop. Moderate conductor.
Opt. Prop. R.I. high, $\alpha = 1.692$, $\beta = 1.702$, $\gamma = 1.705$. Birefringence low, $\gamma - \alpha = 0.013$. Optically biaxial, negative.
Optic axial plane parallel to (010). Straight extinction. Pleochroism marked in the more ferriferous varieties: red or reddish-yellow to green.
Characters in Sediments. Not a common mineral in sediments as a rule, though it may occur locally under suitable conditions, when it assumes a somewhat ragged prismatic character, usually pleochroic and often full of minute inclusions (schiller structure) which may be iron ores or a form of titanium oxide.
Possible Sources of Derivation. Basic and ultrabasic igneous rocks.

Remarks.—The less ferriferous variety of orthorhombic pyroxene, Enstatite, is even rarer in detrital sediments than hypersthene. The former, if occurring, is distinguished from the latter by its lower R.I. very faint pleochroism, low birefringence (approximately equal to that of quartz), and positive optical sign; enstatite also tends to occur in the non-magnetic residues, whereas hypersthene always appears in the magnetic concentrate.

[N.B. If hypersthene is anticipated in a sample, avoid using strong HCl for clearing grains; some varieties are readily attacked by acid—enstatite being more stable in this respect.]

ILMENITE (Titanoferrite). [Fig. 14

Chem. Comp. $FeTiO_3$.
System. Rhombohedral.
Habit. Euhedral, tabular parallel to (0001).
Structure. Crystalline, or in compact platy masses.
Cleavage. None. Parting sometimes developed in twin crystals.
Fracture. Conchoidal.
Hardness. 5 to 6.
Spec. Grav. 4.5 to 5.
Lustre. Submetallic, often with crimson or purplish sheen.
Colour. Iron-black.
Mag. Prop. Moderately magnetic.
Elect. Prop. Good conductor.
Opt. Prop. Opaque, purplish-brown in very thin section.
Characters in Sediments. Commonly occurring in irregular, subangular grains, with characteristic purple or crimson submetallic lustre in reflected light. Grains quite opaque in transmitted light. Partial alteration to leucoxene (q.v.)† frequently observed.
Possible Sources of Derivation. Igneous rocks, especially basic and ultrabasic types.

Remarks. — Ilmenite frequently presents characters which render discrimination between it and associated magnetite a matter of great difficulty under the microscope. Strong artificial incident light may aid its identification, and an initial concentration can also be effected by extracting the magnetite with a powerful horse-shoe magnet. Where partial alteration to leucoxene occurs, there is little fear of confusion.

† See page 59.

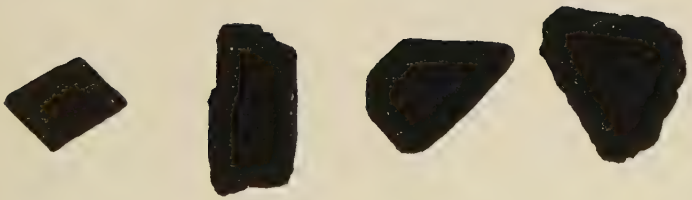

FIG. 14. ILMENITE.

1-3. Demerara, British Guiana. [x 60.]
4. Alluvials, Ceylon. [x 20.]

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KAOLINITE.

Chem. Comp. $Al_2O_3.2SiO_2.2H_2O$.
System. Monoclinic.
Habit. Flattened parallel to (001); pseudo-hexagonal or rhombohedral plates.
Structure. Commonly amorphous, powdery or in laminated aggregates; more rarely crystalline.
Cleavage. Perfect basal, parallel to (001).
Fracture. Irregular.
Hardness. 2 to 2.5.
Spec. Grav. 2.6 to 2.63.
Lustre. Pearly on (001) face, otherwise dull or earthy.
Colour. White, yellow or brown. Translucent.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. low, 1.563 (mean value). Birefringence low, $\gamma - \alpha = 0.008$ approximately. Optically biaxial, negative. Optic axial plane perpendicular to (010). *Bxa* inclined at 20° to the normal to (001).
Characters in Sediments. Commonly occurring as irregular, colourless aggregates or as pseudo-rhombohedral scaly masses, characteristic of the light material of the sediment.
Possible Sources of Derivation. Altered acid igneous and aluminous rocks.

Remarks.—Kaolinite may sometimes be confused with muscovite, from which it may be distinguished by its lower R.I., birefringence, and by absence of good interference figure (characteristic of mica) in (001) cleavage flakes.

KYANITE (Disthene). [Fig. 15

Chem. Comp. $Al_2O_3.SiO_2$.

System. Triclinic.

Habit. Elongated prismatic crystals with irregular terminations. Fibrous.

Cleavage. Perfect parallel to (100), fair parallel to (010), trace parallel to (001). Parting planes parallel to (001) and ($\bar{3}08$) in twin crystals.

Fracture. Ragged.

Hardness. Varies from 4 to 7 with direction: 4 to 5 on (100) parallel to length of crystal, 7 on (010).

Spec. Grav. 3.559 to 3.675, being higher in coloured varieties.

Lustre. Vitreous, pearly.

Colour. Colourless, white, greyish-green, blue. Transparent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. very high, $\alpha = 1.7171$, $\beta = 1.7222$, $\gamma = 1.7290$.

Birefringence low, $\gamma - \alpha = 0.0119$. Optically biaxial, negative.

Optic axial plane inclined at 30° to prism edge (100) (010).

Bxa almost normal to (100). $2V = 82°10'$. Oblique extinction, about 30° from prism edge. Pleochroism slight in deeply coloured varieties: dark to light blue.

Characters in Sediments. Varies greatly in physical characters, the commonest type being the subangular prismatic grain (100), elongated in the direction of the principal axis, irregularly terminated, and with or without traces of the (001) cleavage at right angles to the length of the grain. A more abraded form gives rise to the short "stumpy" grain, usually well rounded and sometimes exhibiting re-entrants due to fracture of the prism face. Compound cleavage fragments, due to differential abrasion of (100) and (010) are often observed, re-entrants in such cases being very marked; these fragments are usually sharply angular. Grains flattened parallel to (010) are rare: they give straight extinction, and do not show the interference figure so typical of the (100) grains. Pleochroic grains are extremely rare. In some of the older sedimentary deposits "shimmer-aggregates" are commonly

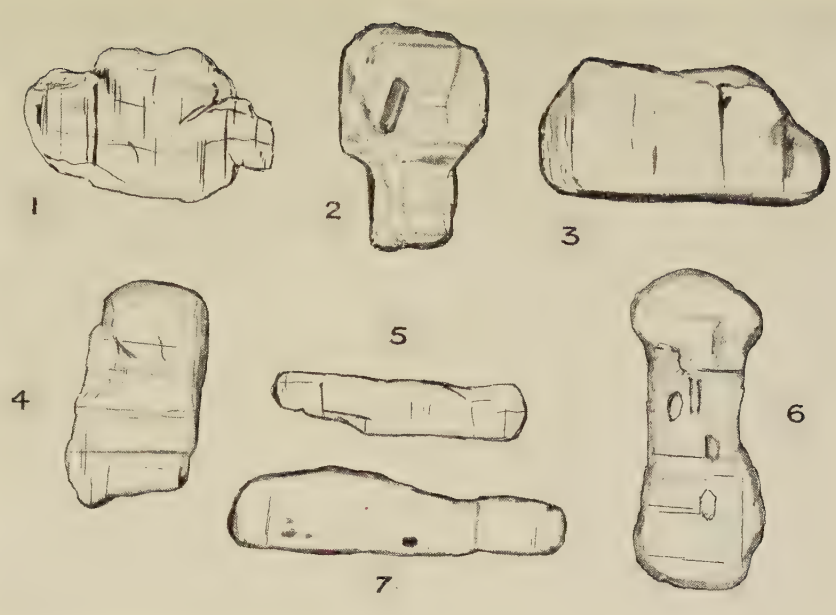


FIG. 15. KYANITE.

1, 7. Lower Greensand, N.W. Wiltshire.
2, 3. Alluvials, West Africa.
4, 6. Bagshot Sands, Hampstead Heath, London.
5. Pliocene Sands, St. Agnes, Cornwall. [All x 60.]

To face page 58.

found; these consist of colourless cores of kyanite surrounded by cryptocrystalline micaceous material, containing abundant inclusions. Such aggregates are, for the most part, decomposition products of kyanite and allied aluminous silicates.†

Possible Sources of Derivation. Metamorphic rocks, especially mica schists and certain gneisses.

Remarks.—Owing to the variety of forms presented by this mineral in sediments, it is a valuable species for correlation purposes, since detailed study shows that certain types are characteristic of definite horizons. Kyanite frequently affords direct evidence of the source of origin of the material in which it occurs, and by the degree of abrasion suffered it may signify the nature and potency of the transporting medium. It is found associated with garnet, staurolite and corundum in many instances, both in metamorphic rocks and in detrital sediments.

† Thomas, H. H., Q.J.G.S., vol. lviii., 1902, p. 627.

LEUCOXENE. [Fig. 13

Chem. Comp. A decomposition product of Ilmenite, as yet ill-defined. It is probably for the most part a form of Sphene (Titanite) q.v.,* with possibly some carbonate. It has been described as a form of Anatase or Perovskite.§

System. Non-crystalline.

Habit. Irregular aggregates or as pseudomorphs after ilmenite.

Structure. Amorphous.

Spec. Grav. Varies from 3.5 to 4.5.

Lustre. Dull.

Colour. White, yellow or brown. Translucent to opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. High R.I., and birefringence, seen in translucent flakes.

Characters in Sediments. Commonly occurs as rounded grains, opaque in transmitted light, white or yellowish-white in reflected light. Sometimes a core of unaltered ilmenite may be observed, in which case the grain will

* See page 76.

§ Iddings: Rock Minerals, 1906, p. 504.

appear weakly magnetic. A rough " pitted " surface is characteristic of most grains, best seen by reflected light. Where the mineral is reasonably translucent, aggregate polarisation may be observed with crossed nicols.

Possible Sources of Derivation. Essentially from ilmenite, and largely *in situ.*

LIMONITE.

Chem. Comp. $2Fe_2O_3.3H_2O$.
System. Non-crystalline.
Habit. Varied; pseudomorphous after iron ores.
Structure. Amorphous, earthy.
Fracture. Uneven.
Hardness. 5.5.
Spec. Grav. 3.8.
Lustre. Submetallic, dull.
Colour. Dark brown, yellowish-brown.
Mag. Prop. Varies according to degree of alteration of the original mineral from which it was derived; essentially non-magnetic *per se.*
Elect. Prop. Moderate conductor.
Opt. Prop. Opaque.
Characters in Sediments. Of frequent occurrence as irregular grains and as powdery aggregates. It has a dull brown colour by reflected light, being opaque in transmitted light except in very thin sections, when a brownish-yellow colour prevails. The translucent particles are isotropic. Limonitic pseudomorphs after marcasite, pyrites, magnetite and hæmatite are not uncommon, while its occurrence as a decomposition product of glauconite is often observed. It represents one of the most prevalent forms of authigenous material found in sediments.
Possible Sources of Derivation. Iron ores of varying composition. Iron-bearing minerals.

Remarks.—Limonite is the commonest type of cement found coating detrital particles, and its removal, prior to their microscopical analysis, necessitates the usual preliminary treatment of a sample with dilute HCl.

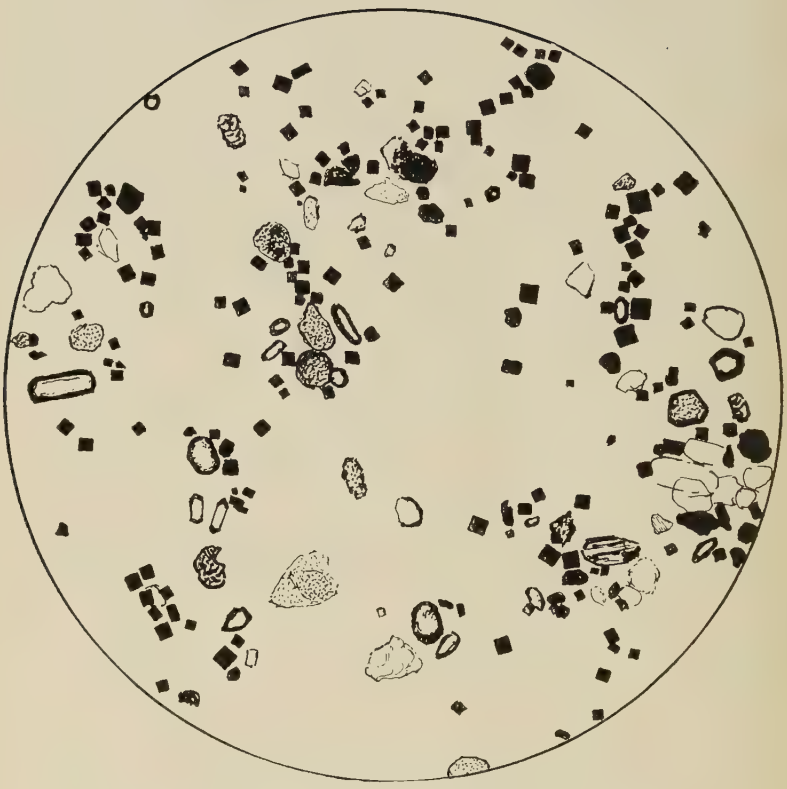


FIG. 16. CONCENTRATE.

Upper Bunter Sands, Hinksford, Staffordshire. [x 25.]
Magnetite, Tourmaline, Staurolite, Garnet, Zircon, Rutile and Muscovite.
(See Page 6.)

To face page 61.

MAGNETITE. [Fig. 16

Chem. Comp. Fe_3O_4.
System. Cubic.
Habit. Octahedral, dodecahedral (sometimes with striations parallel to major diagonal of crystal face), or twinned on (111).
Structure. Crystalline, granular, massive.
Cleavage. None. Parting parallel to (111).
Fracture. Subconchoidal, uneven, hackly.
Hardness. 5.5 to 6.5.
Spec. Grav. 5.168 to 5.180.
Lustre. Metallic, submetallic, dull.
Colour. Silver-grey.
Mag. Prop. Strongly magnetic.
Elect. Prop. Good conductor.
Opt. Prop. Opaque.
Characters in Sediments. The rounded octahedral lustrous grains of this ubiquitous species are very characteristic. Careful examination of the grains with powerful incident light and high power objective frequently reveals the presence of minute facets. In the absence of such faceting, the grains have only a dull grey lustre. Both angular fragments and well rounded irregular grains are also common, the former often showing a marked hackly fracture. Partial alteration to limonite is frequently observed.
Possible Sources of Derivation. Basic and ultrabasic igneous rocks.

Remarks. — Distinguished from ilmenite by its lustre and crystalline form if developed, and may be separated from that mineral by using a horse-shoe magnet.

MARCASITE.

Chem. Comp. FeS_2.
System. Orthorhombic.
Habit. Commonly twinned, simple crystals rare.
Structure. Crystalline, fibrous, concretionary and radiating.
Cleavage. Poor parallel to (110), very imperfect parallel to (011).
Fracture. Uneven, ragged. (Very brittle.)
Hardness. 6.
Spec. Grav. 4.8.
Lustre. Metallic, splendent.
Colour. Brass-yellow.
Mag. Prop. Weakly magnetic.
Elect. Prop. Good conductor.
Opt. Prop. Opaque.
Characters in Sediments. Grains usually small, very ragged and possessing a typical brass-yellow metallic lustre in reflected light; superficial alteration to limonite is commonly shown.
Possible Sources of Derivation. Metalliferous veins; sedimentary rocks, especially chalk.

Remarks.—Much less common than its isomer pyrites, being easily decomposed. Molluscan fragments preserved in marcasite sometimes found.†

† Boswell, P. G. H., Q.J.G.S., vol. lxxi., 1915, p. 581.

MICROCLINE.

Chem. Comp. $K_2O.Al_2O_3.6SiO_2$.
System. Triclinic.
Habit. Prismatic, frequently twinned.
Structure. Crystalline, massive.
Cleavage. Distinct parallel to (001), imperfect parallel to (010), more rarely parallel to (110) and ($\bar{2}01$). Parting parallel to (100) occasionally seen.
Fracture. Conchoidal, uneven.
Hardness. 6 to 6.5.
Spec. Grav. 2.54 to 2.57.
Lustre. Vitreous.
Colour. White, yellow, green or red.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. low, $\alpha = 1.5224$, $\beta = 1.5264$, $\gamma = 1.5295$. Birefringence low, $\gamma - \alpha = 0.0071$. Optically biaxial, negative.
Optic axial plane nearly perpendicular to (010). *Bxa* inclined at small angle ($<5°$) to normal of (001). $2V = 83°$. (001) flakes give oblique extinction, 16°, and (010) flakes give 5°, measured from the trace of (010) and (001) cleavages respectively. (001) plates invariably show characteristic "cross-hatched" structure, due to combination of albite and pericline twinning.
Characters in Sediments. Platy basal grains are the most common, easily recognised by the characteristic "cross-hatching." Grains frequently turbid from decomposition. Other forms, such as (010) cleavage fragments, are rarer. In all cases the grains present highly irregular outlines.
Possible Sources of Derivation. Acid igneous rocks. Metamorphic rocks.

Remarks.—Detrital microline is not particularly common, but where it does occur there is little chance of confusing it with any other species. Inclusions are sometimes seen; these may be primary muscovite (distinct from that occurring as a decomposition product), zircon, iron ores or quartz. Decomposition to muscovite or kaolinite renders grains greyish-white by reflected light, and causes the appearance of highly polarising aggregates between crossed nicols.

MONAZITE. [Fig. 17

Chem. Comp. $(Ce,La,Di)PO_4$.
System. Monoclinic.
Habit. Small crystals flattened parallel to (100) with varying terminations.
Structure. Crystalline, granular.
Cleavage. Perfect parallel to (001), good parallel to (100), less commonly parallel to (010), rarely parallel to $(\bar{1}11)$.
Fracture. Uneven, conchoidal.
Hardness. 5 to 5.5.
Spec. Grav. 4.9 to 5.3.
Lustre. Resinous.
Colour. Yellow, yellowish-brown, red. Translucent to opaque.
Mag. Prop. Weakly magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. high, $\alpha = 1.7957$, $\beta = 1.7965$, $\gamma = 1.8411$. Birefringence high, $\gamma - \alpha = 0.0454$. Optically biaxial, positive.

Optic axial plane perpendicular to (010), almost parallel to (100). *Bxa* inclined to principal axis at angle of 4°. $2E = 24°$. Pleochroism seen in thick grains: light yellow to greenish-yellow.

Characters in Sediments. Usually occurring as well rounded yellow grains with dark border, due to R.I. effect. Decomposition frequently noted, occasioning deep brown coloured patches, which are probably complex alteration products of didymium and cerium. Both colourless and almost opaque grains are found, the former being rare. Grains are mostly (001) cleavage fragments, and yield good interference figure; grains exhibiting recognisable crystal faces are less common, though subangular (100) forms sometimes occur. Some grains are markedly pleochroic.

Possible Sources of Derivation. Acid igneous rocks, especially granites.

Remarks.—Usually there is little difficulty in recognising monazite under the microscope, but if necessary, confirmation may be obtained both chemically and spectroscopically. In the former case the phospho-molybdate reaction is sought, and in the latter case the absorption spectrum with the characteristic didymium bands is easily identified.

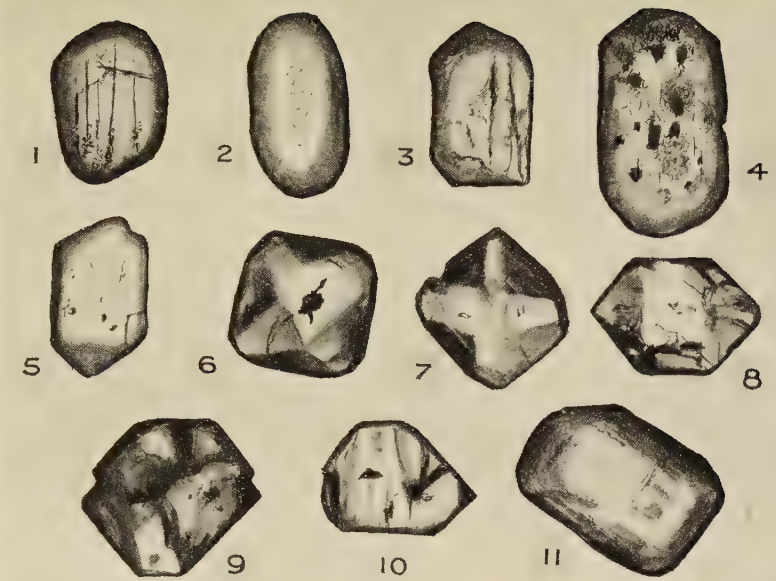


FIG. 17. MONAZITE.

1, 2. Recent Sands, Cape Comorin, Travancore, India. [x 70.]
3-5. Recent Sands, Ceylon. [x 40.]
6-11. Alluvials, Brazil. [x 70.]

To face page 64.

MUSCOVITE.

Chem. Comp. $H_2KAl_3(SiO_4)_3$.
System. Monoclinic.
Habit. Tabular crystals, parallel to (001). Pseudo-orthorhombic or pseudo-rhombohedral forms found.
Structure. Well laminated, massive; individual crystals rare.
Cleavage. Extremely perfect parallel to (001). Parting parallel to (010) and ($\bar{1}11$).
Fracture. Ragged, but rare.
Hardness. 2 to 2.5.
Spec. Grav. 2.76 to 3.
Lustre. Vitreous, pearly.
Colour. Colourless to yellow, deepening with thickness.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. low, $\alpha = 1.5609$, $\beta = 1.5941$, $\gamma = 1.5997$. Birefringence high, $\gamma - \alpha = 0.0388$, but that usually seen in cleavage (001) flakes is due to $\gamma - \beta = 0.0056$, and hence is very low. Optically biaxial, negative. Optic axial plane is normal to (010). *Bxa* practically normal to (001), hence cleavage plates always yield good figure, 2E varying from 56° to 75°.
Characters in Sediments. Commonly in thin, colourless platy grains (001), with characteristic low R.I., bluish-grey birefringence and good figure. Other forms extremely rare. Grains usually rounded. Inclusions are common, such as zircon, rutile, tourmaline and garnet. Undulose extinction is a feature of some varieties.
Possible Sources of Derivation. Igneous and metamorphic rocks.

Remarks. — It is frequently found that two forms of muscovite occur in sediments, one with s.g.$<$2.80, and the other with s.g.$>$2.80; this occasions the appearance of the mineral in both the " light " and " heavy " concentrates. The lighter variety may possibly be a form of leached biotite.

OLIVINE.

Chem. Comp. $(Mg,Fe)_2.SiO_4$.
System. Orthorhombic.
Habit. Flattened prismatic crystals parallel to (100) or (010) with bipyramidal and basal terminations.
Structure. Crystalline.
Cleavage. Poor parallel to (010) and (100).
Fracture. Conchoidal.
Hardness. 6.5 to 7.
Spec. Grav. 3.27 to 3.37.
Lustre. Vitreous, resinous.
Colour. Green, olive-green, dark green, brown.
Mag. Prop. Weakly magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. high, $\alpha = 1.6720$, $\beta = 1.6899$, $\gamma = 1.7089$. Birefringence high, $\gamma - \alpha = 0.0369$. Optically biaxial, positive or negative. Optic axial plane parallel to (001). *Bxa* either normal to (100) or (010) according to amount of FeO present; in former case crystal is positive, in the latter case it is negative. Non-pleochroic. Grains elongated parallel to principal axis give straight extinction.
Characters in Sediments. Usually occurs as irregular and much fractured grains, showing traces of decomposition. The normal colour tends to be bleached to a yellowish-green tint. Grains are often fractured parallel to (100), and frequently show positive biaxial interference figure, with large optic axial angle.
Possible Sources of Derivation. Basic and ultra-basic igneous rocks.

Remarks.—A comparatively rare detrital mineral, usually found in recent deposits (such as shore-sands or dune-sands) occurring in the vicinity of ultra-basic rock masses.

ORTHOCLASE.

Chem. Comp. $K_2O.Al_2O_3.6SiO_2$.
System. Monoclinic.
Habit. Prismatic, often twinned (Carlsbad [001] or Baveno (021)).
Structure. Crystalline.
Cleavage. Perfect parallel to (001), good parallel to (010), imperfect parallel to (110).
Fracture. Conchoidal.
Hardness. 6 to 6.5.
Spec. Grav. 2.54 to 2.56.
Lustre. Vitreous.
Colour. Colourless, grey or reddish-white.
Mag. Prop. Non-magnetic.
Elect. Prop. Non-conductor.
Opt. Prop. R.I. low, $\alpha = 1.5194$, $\beta = 1.5236$, $\gamma = 1.5263$. Birefringence low, $\gamma - \alpha = 0.0069$. Optically biaxial, negative. Optic axial plane normal to (010). *Bxa* inclined at 85° to normal of (001). $2E = 120°$. (001) plates show straight extinction, (010) plates give extinction angle of 5°.
Characters in Sediments. Irregular or fractured grains frequently flattened parallel to (001) are the usual types met with in the " lighter " portions of clastic sediments. Secondary muscovite or kaolin clouding the grains is a common feature. Grains showing Carlsbad twinning are sometimes met with. Distinction from quartz, where such twinning is absent, is sometimes a matter of difficulty.
Possible Sources of Derivation. Acid igneous rocks, pegmatite veins.

PLAGIOCLASE.

Chem. Comp. Isomorphous group of felspars varying from Albite ($Na_2O.Al_2O_3.6SiO_2$) to Anorthite ($CaO.Al_2O_3.2SiO_2$).

System. Triclinic.

Habit. Tabular, prismatic, commonly twinned on either Albite law (010), Pericline law (about y axis), Carlsbad law (about z axis), Baveno law (021) or Manebach law (001).

Structure. Crystalline, massive.

Cleavage. Perfect parallel to (001), imperfect parallel to (010), rarely parallel to (110). Parting parallel to (100).

Fracture. Conchoidal, irregular.

Hardness. 6 to 6.5.

Spec. Grav. 2.605 (Albite) to 2.765 (Anorthite).

Lustre. Vitreous, pearly.

Colour. Colourless, grey, greyish-white.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductors.

Opt. Prop. R.I. low, (Albite) $\alpha = 1.5290$, $\beta = 1.5333$, $\gamma = 1.5386$. (Anorthite) $\alpha = 1.5752$, $\beta = 1.5833$, $\gamma = 1.5884$. Birefringence low, (Albite) $\gamma - \alpha = 0.0096$, (Anorthite) $\gamma - \alpha = 0.0132$.

Optical properties vary with composition, albite being biaxial, positive, and anorthite biaxial, negative. Extinction oblique, varying in (001) grains from 4° in albite to 37° in anorthite, and in (010) grains from 18° in albite to 36° in anorthite. [See Iddings, op. cit., p. 221, et seq.]

Characters in Sediments. Grains characterised by irregular outline, presence of twin lamellæ and superficial decomposition products such as muscovite in case of albite felspar, and saussurite in case of anorthite felspar. Distinction between various intermediate members of the group is in most cases impossible with single grains unless very definite crystal faces yielding recognisable optical criteria are shown, though the R.I. is frequently a clue, being lower than Canada balsam for albite and oligoclase, and higher for andesine, labradorite, bytownite and anorthite. Decomposition products often mask optical characters.

Possible Sources of Derivation. Igneous rocks.

Remarks.—The most commonly occurring member of the group in sediments seems to be Oligoclase, the more lime-bearing felspars being easily altered. Microperthite grains have also been noted.

PYRITES.

Chem. Comp. FeS_2.
System. Cubic.
Habit. Cubic, dodecahedral, " pyritohedral " and combinations of different forms. Sometimes twinned (interpenetrant), cubic faces frequently striated.
Structure. Crystalline, massive.
Cleavage. Bad, parallel to (100) and (111).
Fracture. Conchoidal.
Hardness. 6 to 6.5.
Spec. Grav. 4.967 to 5.100.
Lustre. Metallic, splendent.
Colour. Brass-yellow, sometimes tarnished.
Mag. Prop. Non-magnetic.
Elect. Prop. Good conductor.
Opt. Prop. Opaque.
Character in Sediments. Frequently occurs as well rounded dodecahedral or " pyritohedral " grains, less commonly as irregular conchoidal grains. The brass-yellow colour and lustre by reflected light are very characteristic, as is also the tarnish (a dull blackish-brown veneer) due to alteration, probably to limonite. Simple cubic grains are rare.
Possible Sources of Derivation. Igneous and sedimentary rocks, metalliferous veins.

Remarks. — Pyrites is more common in detrital sediments than its isomer marcasite (q.v.), except in certain local cases.† It may be removed from sediments (if necessary) by boiling with weak HNO_3.

† Boswell, P. G. H., Q.J.G.S., vol. lxxi., 1915, p. 577.

PYROLUSITE.

Chem. Comp. MnO_2.
System. Doubtful (?Orthorhombic).
Habit. Probably pseudomorphous after manganite.
Structure. Normally amorphous, massive.
Cleavage. None.
Fracture. Splintery, uneven.
Hardness. 2 to 2.5.
Spec. Grav. 4.75.
Lustre. Metallic, dull.
Colour. Purplish-black.
Mag. Prop. Weakly magnetic.
Elect. Prop. Moderate conductor.
Opt. Prop. Opaque.
Characters in Sediments. Usually occurs in the form of irregular purplish-black grains, void of all crystalline structure.
Possible Sources of Derivation. Of secondary origin, derived by oxidation of manganese present in various rocks; metalliferous veins; organic.

Remarks.—Pyrolusite occurs chiefly as an authigenous constituent of detrital sediments, also frequently as dendritic aggregates on the joint planes of sediments, and on individual pebbles. Confirmed by chemical test: borax bead attains a violet-red colour in oxidising flame; fused with Na_2CO_3, yields a bluish-green mass.

PYRRHOTITE.

Chem. Comp. $Fe_xS_{(x+1)}$, with impurities such as Cu, Ni and Co.
System. Hexagonal.
Habit. Tabular, prismatic with pyramidal terminations.
Structure. Massive, less commonly crystalline.
Cleavage. Fair, parallel to (0001), bad parallel to (11$\bar{2}$0).
Fracture. Uneven.
Hardness. 3.5 to 4.5.
Spec. Grav. 4.58 to 4.64.
Lustre. Metallic.
Colour. Bronze-yellow, reddish-yellow.
Mag. Prop. Strongly magnetic.
Elect. Prop. Good conductor.
Opt. Prop. Opaque.
Character in Sediments. This species, when present in detrital sediments, is always very irregular (ragged) in form, and exhibits a characteristic bronze lustre in reflected light.
Possible Source of Derivation. Basic igneous rocks; metalliferous veins.

Remarks.—Relatively uncommon in detrital sediments, but when present it is apparent from the preliminary examination of the sample. It is readily dissolved in HCl, and therefore does not appear in the cleaned " heavy " residue. Its highly magnetic properties and lustre serve to distinguish it from pyrites and chromite, with which it may possibly be confused.

QUARTZ. [Figs. 18 & 19

Chem. Comp. SiO_2.
System. Rhombohedral.
Habit. Prismatic, with positive and negative rhombohedron terminations.
Structure. Crystalline, cryptocrystalline, massive.
Cleavage. Rare parallel to $(10\bar{1}1)$ and $(01\bar{1}1)$.
Fracture. Conchoidal.
Hardness. 7.
Spec. Grav. 2.660.
Lustre. Vitreous.
Colour. Colourless, purple, black, pink, yellow. Transparent to translucent.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. low, $\epsilon = 1.55328$, $\omega = 1.54418$.
Birefringence low, $\epsilon - \omega = 0.0091$.
Optically uniaxial, positive. Prismatic sections give straight extinction.
Characters in Sediments. Very variable in form and size, but usually in subangular, irregular grains unless occurring in æolian deposits, when the roundness of the grains is very marked. Frequently inclusions are present, either fluid or mineral; the latter may be either rutile, apatite, ilmenite, sillimanite, tourmaline, zircon or iron ores, the former being gaseous or liquid. Grains often exhibit undulose extinction, due to strain.
Probable Sources of Derivation. Acid and intermediate rock types, more rarely basic. Sedimentary and crystalline metamorphic rocks. Metalliferous veins.

Remarks.—Quartz is one of the most important constituents of detrital sediments, especially of the arenaceous and argillaceous types. Its detailed study in the " lighter " portion of the sediment is of great consequence, particularly when inclusions † are present; these are, by their nature and abundance, frequently valuable indices for correlation purposes.

† Mackie, W., Trans. Edin. Geol. Soc., vol. vii., 1897, pp. 148-172.
Teall, J. J., " North-West Highlands of Scotland," Mem. Geol. Surv., 1907, p. 54.
Gilligan, A., Q.J.G.S., vol. lxxv., 1919, p. 260.

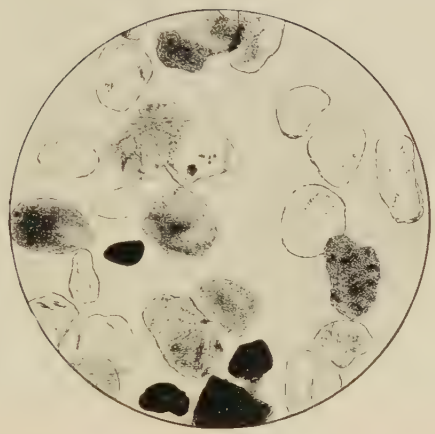


FIG. 18. QUARTZ.
Blown Sand, Newgale, Pembrokeshire. [x 25.]
N.B.—Note degree of rounding.

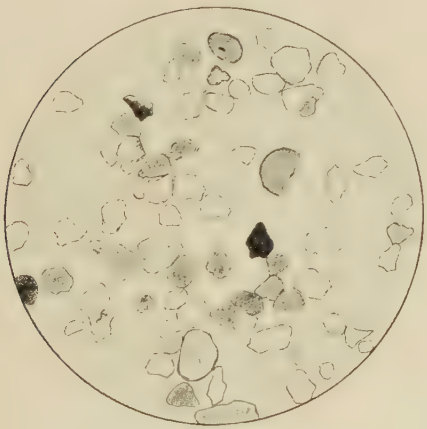


FIG. 19. QUARTZ.
Tunbridge Wells Sand, Eridge, Sussex. [x 15.]

To face page 72.

RUTILE. [Fig. 20

Chem. Comp. TiO_2.
System. Tetragonal.
Habit. Prismatic, acicular. Frequently striated parallel to principal axis, with transverse striæ parallel to (101) due to polysynthetic twinning. Sometimes twinned about (101), either geniculate or as a network (sagenite).
Structure. Crystalline.
Cleavage. Good parallel to (110) and (100). Occasionally parallel to (111).
Fracture. Subconchoidal.
Hardness. 6 to 6.5.
Spec. Grav. 4.18 to 4.25.
Lustre. Metallic to vitreous.
Colour. Red, reddish-brown, yellow.
Mag. Prop. Non-magnetic.
Elect. Prop. Moderately good conductor.
Opt. Prop. R.I. very high, $\epsilon = 2.9029$, $\omega = 2.6158$.
Birefringence high, $\epsilon - \omega = 0.2871$.
Optically uniaxial, positive. Interference figure anomalous in twinned crystals. Red and brown varieties usually pleochroic, weak : reddish-brown to brown or yellow. Maximum absorption direction parallel to principal axis. Straight extinction.
Characters in Sediments. Two types of rutile are frequently met with, one being that of well-formed prismatic grains with pyramidal terminations slightly rounded, the other, that of sharply angular fractured grains; the former are usually " foxy-red," reddish-brown or yellow in colour, the latter being more commonly of an amber tint. In addition, geniculate twins are found in certain sands, especially in alluvials, the two individuals making an angle of about 65° with one another. The degree of rounding of grains is a variable factor, often being very slight when compared with associated minerals of similar hardness and stability.
Possible Sources of Derivation. Acid igneous rocks, crystalline metamorphic rocks. Frequently derived *in situ* from the decomposition of ilmenite.

SIDERITE (Chalybite).

Chem. Comp. $FeCO_3$.
System. Rhombohedral.
Habit. Simple rhombohedron, often with curved faces.
Structure. Crystalline, massive, compact.
Cleavage. Perfect rhombohedral, parallel to $(10\bar{1}1)$.
Fracture. Uneven.
Hardness. 3.5 to 4.
Spec. Grav. 3.83 to 3.88.
Lustre. Vitreous, dull.
Colour. Shades of brown or grey. Translucent.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. high, $\omega = 1.8724$, $\epsilon = 1.6338$. Birefringence very high, $\omega - \epsilon = 0.2386$. Optically uniaxial, negative.
Characters in Sediments. Subangular or rounded rhombohedral plates determined principally by cleavage.
Possible Sources of Derivation. Clay ironstone and allied stratified deposits, also from metalliferous veins.

Remarks.—By no means a common mineral in detrital sediments, only occurring locally under suitable conditions.

FIG. 20. RUTILE.

1, 6, 7. Lower Greensand, N.W. Wiltshire. [x 70.]
2-4. Tunbridge Wells Sand, Kent. [x 60.]
5. Geniculate twin, Tunbridge Wells Sand, Kent. [x 100.]
8. Recent Sands, Ceylon. [x 70.]

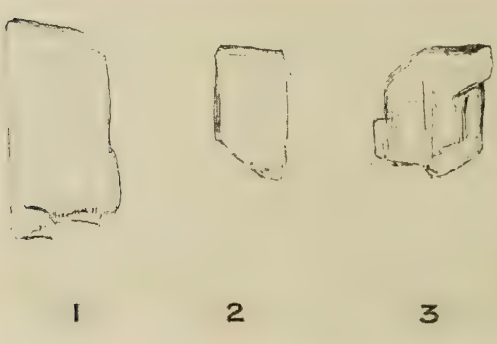


FIG. 21.

1-3. Sillimanite. [All x 70.]

To face page 75.

SILLIMANITE. [Fig. 21

Chem. Comp. $Al_2O_3.SiO_2$.
System. Orthorhombic.
Habit. Prismatic, with irregular terminations, fibrous. Sometimes striated.
Structure. Crystalline.
Cleavage. Good parallel to (010).
Fracture. Irregular.
Hardness. 6 to 7.
Spec. Grav. 3.23 to 3.24.
Lustre. Vitreous.
Colour. Pale shades of brown, green, or grey. Sometimes colourless. Transparent.
Mag. Prop. Non-magnetic.
Elect. Prop. Non-conductor.
Opt. Prop. R.I. high, $\alpha = 1.6603$, $\beta = 1.6612$, $\gamma = 1.6818$.
Birefringence high, $\gamma - \alpha = 0.0215$.
Optically biaxial, positive. *Bxa* normal to (001).
Optic axial plane parallel to (010). $2E = 42^\circ\ 30'$ (varies).
Straight extinction parallel to the prism edge. Occasionally pleochroic, especially if much coloured : dark to pale shade.
Characters in Sediments. Usually found as long slender prisms or fibres, sometimes flattened, with fractured or irregular terminations. Flattened grains parallel to (001) exhibit good biaxial figure and low birefringence due to $\beta - \alpha = 0.0009$. Grains with regular striations are comparatively rare; curved forms are occasionally met with.
Possible Sources of Derivation. Crystalline metamorphic rocks.

Remarks.—Sillimanite is essentially a local species. It is distinguished from topaz and andalusite by its higher birefringence and smaller axial angle.

SPHENE (Titanite).

Chem. Comp. $CaO.SiO_2.TiO_2$.
System. Monoclinic.
Habit. Euhedral, prismatic, diamond-shaped (flattened parallel to (001)). Frequently twinned.
Structure. Crystalline.
Cleavage. Good parallel to (110), imperfect parallel to (100) and ($\bar{1}12$), rare parallel to (111). Parting parallel to (221) twin lamellæ.
Fracture. Irregular.
Hardness. 5 to 5.5.
Spec. Grav. 3.4 to 3.56.
Lustre. Vitreous.
Colour. Brown, brownish-yellow. Translucent.
Mag. Prop. Non-magnetic.
Elect. Prop. Moderate conductor.
Opt. Prop. R.I. high, $\alpha = 1.8874$, $\beta = 1.8940$, $\gamma = 2.0093$. Birefringence very high, $\gamma - \alpha = 0.1219$. Optically biaxial, positive. Optic axial plane parallel to (010). *Bxa* practically normal to (102). Optic axial angle small but variable, $2E = 52\frac{1}{2}^\circ$. Occasionally pleochroic in strongly coloured varieties : brown to colourless.
Characters in Sediments. Rounded diamond-shaped grains common, also irregular subangular cleavage fragments, both types often presenting dusky interiors due to decomposition. In grains the pleochroism is usually poor, and brown colouration often much bleached. Some varieties are traversed by a complex network of cracks due partly to fracture and partly to bad cleavage.
Possible Sources of Derivation. Intermediate igneous rocks, metamorphic rocks such as gneisses, schists and altered limestones.

SPINEL.

Chem. Comp. $MgO.Al_2O_3$.
System. Cubic.
Habit. Octahedral
Structure. Crystalline.
Cleavage. Bad parallel to (111).
Fracture. Conchoidal.
Hardness. 8.
Spec. Grav. 3.52 to 3.71 (varies with composition).
Lustre. Vitreous.
Colour. Shades of red, reddish-yellow, in common Spinel; green in Pleonaste (Iron-Spinel).
Mag. Prop. Non-magnetic.
Elect. Prop. Non-conductor.
Opt. Prop. R.I. high, 1.7135 to 1.7260, varying with composition and colour. Isotropic.
Characters in Sediments. Generally occurs as well rounded octahedral grains, much " pitted " from uneven abrasion. The conchoidal fracture, if developed, is very characteristic. Recognised by its high R.I., colour and isotropism.
Possible Sources of Derivation. Metamorphosed limestone, crystalline schist, dolomitic limestone.

STAUROLITE. [Fig. 22

Chem. Comp. Hydrous silicate of iron, magnesium and aluminium.
System. Orthorhombic.
Habit. Prismatic or twinned about (032).
Structure. Crystalline.
Cleavage. Good parallel to (010), rarely parallel to (110).
Fracture. Subconchoidal, " hackly."
Hardness. 7 to 7.5.
Spec. Grav. 3.65 to 3.7.
Lustre. Vitreous.
Colour. Reddish-brown, brownish-yellow, brown.
Mag. Prop. Weakly magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. high, $\alpha = 1.736$, $\beta = 1.741$, $\gamma = 1.746$. Birefringence low, $\gamma - \alpha = 0.010$. Optically biaxial, positive. Optic axial plane parallel to (100). *Bxa* normal to (001). Prismatic sections show straight extinction. Pleochroism moderate : brown to straw-yellow.
Characters in Sediments. Well crystallised grains are comparatively rare, the usual type being irregular or somewhat platy grains determined largely by cleavage, having marked hackly fracture. Intensity of pleochroism varies greatly, maximum colouration being apparent in prismatic grains orientated in an E.-W. position. Inclusions are common, especially quartz; garnet, tourmaline, rutile, biotite and carbonaceous matter have all been observed; such inclusions are usually commoner in the deeper coloured varieties. Dr. Thomas has described some well formed crystals from the New Red Sandstone of the West of England, which are tabular parallel to $\{010\}$, modified by $\{110\}$, and terminated by forms $\{101\}$ and $\{001\}$;† such grains constitute a rare type in sediments generally. An infrequent type, sometimes met with in alluvials, is that of the rounded cruciform twin, the two individuals being disposed at right angles. Superficial decomposition to a form of chlorite or mica may be noted in some instances.
Possible Sources of Derivation. Crystalline schists, contact metamorphic rocks.

Remarks.—Staurolite often occurs in association with garnet, kyanite and sillimanite in metamorphic rocks, this association being common in many sediments thence derived

† Thomas, H. H., Q.J.G.S., vol. lxv., 1909, p. 234.

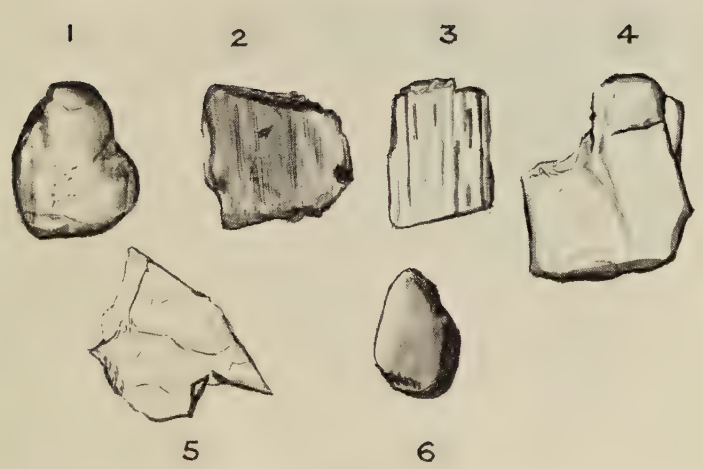


FIG. 22. STAUROLITE.

1. Pliocene Sands, St. Erth, Cornwall.
2. Lower Greensand, N.W. Wiltshire.
3-5. Alluvials, W. Africa.
6. Blown Sand, Newgale, Pembrokeshire.

[All x 70.]

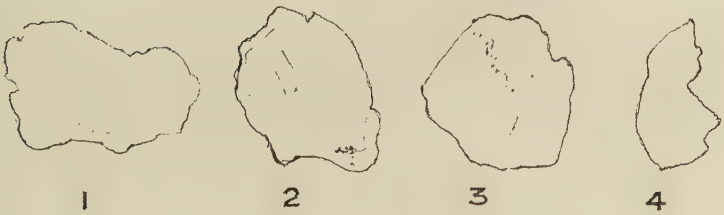


FIG. 23. TOPAZ.

1-4. Miocene Sands, Trinidad. [All x 40.]

To face page 78.

TOPAZ. [Fig. 23

Chem. Comp. $[Al(O,Fe_2)]AlSiO_4$.
System. Orthorhombic.
Habit. Prismatic, with pyramidal terminations, domes and basal plane.
Structure. Crystalline, granular.
Cleavage. Perfect basal parallel to (001), imperfect parallel to (201) and (021).
Fracture. Irregular, subconchoidal.
Hardness. 8.
Spec. Grav. 3.532 to 3.574.
Lustre. Vitreous, subresinous.
Colour. Colourless, yellow, blue, red, green. Transparent.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. high, $\alpha = 1.6155$, $\beta = 1.6181$, $\gamma = 1.6250$. Birefringence low, $\gamma - \alpha = 0.0095$. Optically biaxial, positive. Optic axial plane parallel to (010). *Bxa* normal to (001). $2V \fallingdotseq 60°$ (varies). Prismatic sections give straight extinction.
Characters in Sediments. Subangular or irregular grains are commonest in sediments, well crystallised forms being rare. Basal grains are of frequent occurrence (due to dominant cleavage), and these show good interference figure. Inclusions are not uncommon, these being mostly fluid; ilmenite and hæmatite inclusions have also been observed.
Possible Sources of Derivation. Granite, greisenised and other contact metamorphic rocks.

Remarks. — Topaz is seldom an abundant mineral in sediments, and it tends to be very local. It may sometimes be easily confused with andalusite, which it resembles in certain crystallographic and physical properties; it may be differentiated from that species by its cleavage, absence of pleochroism, optically positive character and transparency, andalusite being so commonly clouded with alteration products.

TOURMALINE. [Fig. 24

Chem. Comp. Complex silicate of boron and aluminium with Fe″,Mg,Mn,Ca,Na,K,Li,F and hydroxyl.

System. Rhombohedral.

Habit. Prismatic, often with vertical striations, irregular.

Structure. Crystalline, massive, compact; frequently radiating or in parallel growth.

Cleavage. Imperfect parallel to $(11\bar{2}0)$ (rhombohedral), and bad parallel to $(10\bar{1}1)$. Basal parting.

Fracture. Subconchoidal.

Hardness. 7 to 7.5.

Spec. Grav. 2.98 to 3.20.

Lustre. Vitreous, resinous.

Colour. Brown, blue, green, brownish-black, pink; rarely colourless.

Mag. Prop. Weakly magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\omega = 1.6424$, $\epsilon = 1.6222$. Birefringence moderate, $\omega - \epsilon = 0.202$. Optically uniaxial negative. Occasionally grains show anomalous biaxial interference figure. Prismatic grains give straight extinction. brown varieties: brown to yellow, dark green to Pleochroism varies with colour, being most intense in mauve, blue to mauve. Maximum absorption in prismatic grains orientated in a N.-S. position.

Characters in Sediments. A ubiquitous species, occurring principally in three forms, prismatic with varied terminations, basal (usually well rounded) and irregular fractured grains. The prismatic varieties may be terminated by rhombohedra and basal parting, but are often void of terminal faces, being frequently bounded by parting or irregular fracture. Pseudo-hexagonal plates flattened parallel to (0001) and modified by $(11\bar{2}0)$ faces have been described,† but are rare; such grains and similar well worn types exhibit good uniaxial interference figure. Colour and pleochroism vary greatly, the brown and dark coloured grains normally showing the strongest pleochroism; blue tourmaline is invariably weak in this respect. Inclusions are often noted, but are generally indeterminable. The mineral is nearly always remarkably free from decomposition products, grains being normally translucent.

Possible Sources of Derivation. Pneumatolytic rocks, acid igneous rocks, pegmatites, schists, gneisses, phyllites.

† Thomas, H. H., Q.J.G.S., vol. lxv., 1909, p. 233.

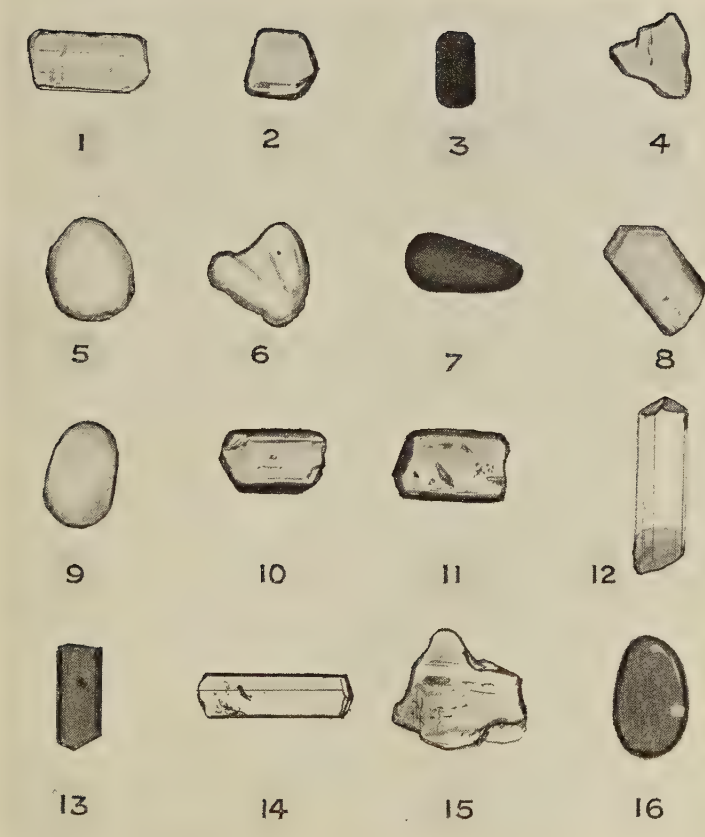


FIG. 24. TOURMALINE.

1–3. Tunbridge Wells Sand, Tunbridge Wells, Kent. [x 70.]
4. Ashdown Sand, Hastings, Sussex. [x 50.]
5, 6. Glacial Sands, Withybush, Haverfordwest, Pembrokeshire. [x 40.]
7. Blown Sand, Newgale, Pembrokeshire. [x 70.]
8. Eocene Sand, Bromley, Kent. [x 70.]
9. Blown Sand, Rosslare, Co. Wexford. [x 40.]
10. Recent Sands, Brazil. [x 70.]
11. Bagshot Sand, Hampstead, London. [x 40.]
12. Moruga Sands (Pliocene), Trinidad. [x 70.]
13, 14. Pliocene Sands, St. Erth, Cornwall. [x 70.]
15, 16. Pliocene Sands, St. Erth, Cornwall. [x 40.]

To face p. 80.

WOLFRAMITE.

Chem. Comp. (Fe,Mn)WO_4.
System. Monoclinic.
Habit. Prismatic, elongated, with vertical striations.
Structure. Massive, compact, rarely crystalline.
Cleavage. Perfect parallel to (010), imperfect parallel to (100).
Fracture. " Splintery," uneven.
Hardness. 5 to 5.5.
Spec. Grav. 7.2 to 7.5.
Lustre. Metallic, dull.
Colour. Black, steel-grey.
Mag. Prop. Moderately magnetic.
Elect. Prop. Good conductor.
Opt. Prop. Opaque in transmitted light, sometimes translucent (brown) in very thin sections or around periphery of grain.
Characters in Sediments. Commonly fragmental, very seldom in the form of crystallised grains. Tabular grains sometimes met with, flattened parallel to (010).
Possible Sources of Derivation. Metalliferous lodes in association in acid igneous intrusions.

Remarks. — Wolframite is easily overlooked in sediments unless its presence is anticipated by reason of local environment.

XENOTIME.

Chem. Comp. YPO_4.
System. Tetragonal.
Habit. Euhedral, prismatic.
Structure. Crystalline.
Cleavage. Perfect parallel to (110).
Fracture. Uneven, irregular.
Hardness. 4 to 5.
Spec. Grav. 4.45 to 4.56.
Lustre. Vitreous.
Colour. Shades of brown, brownish-red, yellow. Translucent.
Mag. Prop. Moderately magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. high, $\epsilon = 1.816$, $\omega = 1.721$. Birefringence high, $\epsilon - \omega = 0.095$. Optically uniaxial, positive. Straight extinction.
Characters in Sediments. Usually occurs as slightly rounded tetragonal prisms, yellowish-brown in colour and somewhat patchy in appearance, owing to decomposition. Worn basal grains are met with, yielding positive uniaxial interference figure. Grains often show (with 1/12th oil immersion objective) small indeterminate inclusions arranged parallel to the principal axis.
Possible Sources of Derivation. Granites, pegmatites, intermediate rocks; less commonly gneiss.

Remarks.—Xenotime is an exceedingly difficult mineral to differentiate from zircon in detrital sediments by ordinary microscopical methods, and recourse has frequently to be made to the spectroscope for its ultimate determination. It differs from zircon in being moderately magnetic (though this property is not always constant), in showing more pronounced zonary structure, also in the paucity of inclusions such as are characteristic of that mineral. The very rare development of either (311) or (201) faces, both often features of zircon grains, is a negative factor to note in the case of xenotime. The mineral is probably far more widespread in occurrence than is at present appreciated, there being the tendency of confusion with coloured zircon. Cloudiness of grains is a feature of xenotime (due to decomposition products of yttrium and possibly cerium, if present) but is not so common in zircon. Confusion with cassiterite or anatase, suggested by some authors, is seldom likely to occur.

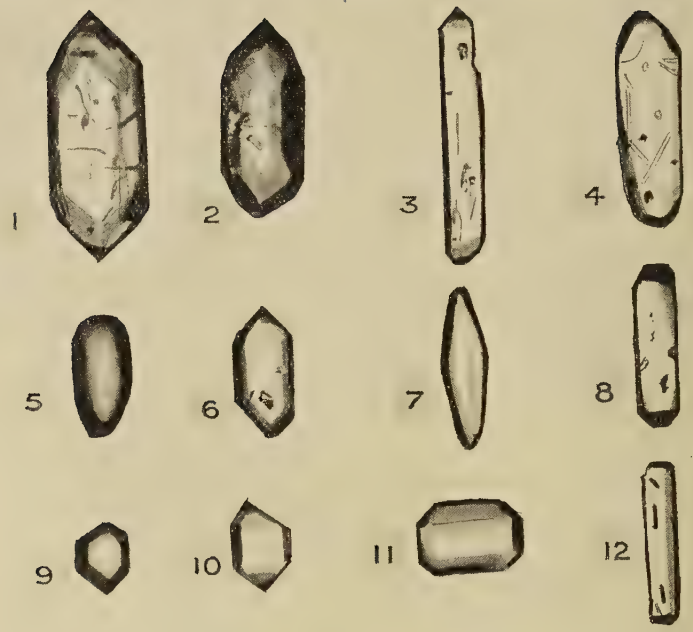


FIG. 25. ZIRCON.

1, 2. Alluvials, W. Africa.
3. Bagshot Sand, Hampstead Heath, London.
4, 5. Lower Greensand, N.W. Wiltshire.
6. Wealden Sand, Shotover Hill, Oxford.
7, 8, 12. Tunbridge Wells Sand, Kent.
9-11. Ashdown Sands, Hastings, Sussex.
[All x 100.]

To face page 83.

ZIRCON. [Fig. 25

Chem. Comp. $ZrO_2.SiO_2$.
System. Tetragonal.
Habit. Euhedral; prismatic; bipyramidal. Sometimes prisms are elongated in the direction of the principal axis. Twinning rare.
Structure. Crystalline.
Cleavage. Imperfect parallel to (110), poor parallel to (111).
Fracture. Conchoidal.
Hardness. 7.5.
Spec. Grav. 4.2 to 4.86.
Lustre. Adamantine, vitreous.
Colour. Colourless, yellowish-brown, green.
Mag. Prop. Non-magnetic.
Elect. Prop. Bad conductor.
Opt. Prop. R.I. high, $\epsilon = 1.9682$, $\omega = 1.9239$. Birefringence high, $\epsilon - \omega = 0.0443$. Optically uniaxial, positive. Occasionally abnormal biaxial crystals are met with. Straight extinction. Pleochroic in strongly coloured varieties.
Characters in Sediments. A common species, varying considerably in form. The prevalent type of grain is colourless, prismatic (100) with pyramidal terminations (111). Less frequently prismatic grains may be noted, modified by faces (110) and capped by pyramids (311) and (111). Basal grains (flattened parallel to (001)) are comparatively scarce. Fractured grains are common, but sharply angular fragments are rare, zircon nearly always exhibiting a certain degree of rounding. Zoning may be observed, while the presence of inclusions, sometimes arranged parallel to the length of the crystal, at other times irregularly distributed, is a common feature. Inclusions may be fluid, glassy, negative crystals, or consist of minerals such as apatite and possibly xenotime. Inclusions within inclusions have also been observed. Occasionally the grains have a dusky appearance, due to the crowding of inclusions, *not* to decomposition products, as suggested by some authors.† Large grains with abnormal optical properties (biaxial interference figures, low birefringence, pleochroism and absence of inclusions) seem to be very local.

† See under Xenotime, p. 82.

Possible Sources of Derivation. Acid and intermediate igneous rocks; less commonly crystalline schists and limestones.

Remarks.—Confusion may arise in some cases in differentiating zircon from xenotime and cassiterite, especially the former (q.v.). Its lustre and lower double refraction serve to distinguish it from cassiterite, spectroscopic methods frequently being necessary in the case of xenotime.

See Krushtchov, Mem. Acad. Imp. Sci. St. Petersb., xliii, No. 3, 1894, and Min. Petr. Mitth., vii, 1886, p. 423; also Mackie, W. (Purple Zircons), Abs. paper read before Edin. Geol. Soc., Geol. Mag., Ap., 1922, p. 184.

CHAPTER III.

THE PRINCIPLES AND PRACTICE OF CORRELATION OF SEDIMENTS BY PETROGRAPHIC METHODS.

The gradual evolution of qualitative and quantitative methods of study of detrital sediments has resulted in the recognition of certain broad principles governing the trend of events during any given cycle of erosion. These principles involve, among others, three fundamental factors contributing to the fulfilment of such a cycle, viz., the weathering of a land-mass, the transportation of the weathered material by mechanical agency, and the accumulation of that material in a suitable basin of deposition, under varying subærial or subaqueous conditions. By their mineralogical composition, the resulting sediments to a greater or lesser extent reflect the nature of the parent rock from which they were derived, and by their physical characteristics, the nature and potency of the transporting media. It is obvious, however, that the question of chemical stability will have a distinct influence on the composition of the newly-formed deposits, since only the more stable mineral species will survive the period of transference from source to seat of deposition. In this way "heavy" residues, *i.e.*, the more stable accessory minerals of rocks, assume an importance which would otherwise be out of all proportion to their frequency of occurrence, either as primary rock-forming species, or as allothigenous constituents of sediments.

According as mechanical or chemical erosion is predominant in any given area, so the record of sedimentation is clear or illegible, the former producing suites of fundamental minerals (*i.e.*, species indicative of and recognisable in the parent rock masses), the latter giving rise to deposits wherein fundamental minerals are either replaced by secondary products as a result of chemical reaction, or are entirely removed by solution. Since the intensity of mechanical erosion normally outweighs in importance chemical erosion, sediments, in particular those designated as arenaceous and argillaceous, tend to retain an individuality which, petrographically speaking, is clearly defined.

We may consider the ideal case of a homogeneous drainage area A, and a restricted lens of deposition B unaffected by extraneous influences such as marine currents. The drainage area A (better known as the "Distributive Province") may be composed of various rock-types, but for simplicity suppose it to be made up of a given

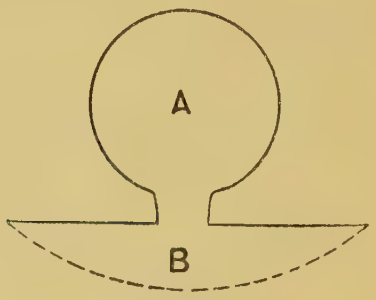


Fig. 26.

igneous rock X. During the progress of denudation, the least stable minerals of X suffer decay and alteration, and in their original form fail to reach B; the more stable species, however, ultimately find their way to B with the result that the mineralogical composition of B shows a marked degree of uniformity, even though it does not faithfully reflect the initial composition of X. We know, however, that such homogeneous areas of drainage and deposition seldom exist in nature, and that contamination from other sources is a normal factor to be reckoned with in all sedimentary provinces. A great deal depends on the proximity of the area undergoing denudation to the basin of deposition; the closer they are together, the more localised are the sediments formed, and mineral suites, by their variation, tend to differentiate contemporaneous deposits in close juxtaposition.

Consider next two distinct distributive provinces (1) and (2) both contributing material to one basin of deposition :—

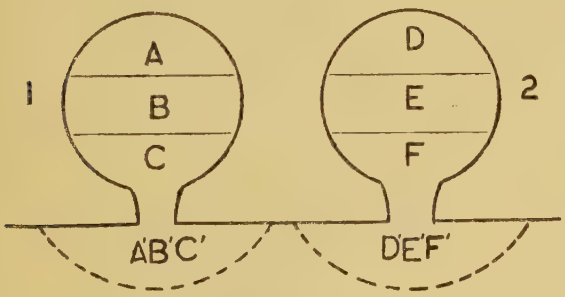


Fig. 27.

A, B, C, D, E and F, represent different rock-types. The initial denudation of (1) and (2) starts, possibly, with C and F respectively; the first types of sediment to be laid down (C′ and F′) will therefore have decided C and F affinities. As the drainage is cut back, B and E contribute material, the transition being marked by sediment with bC and eF affinities respectively (the smaller letter in each case denoting the lesser influence). With the progressive advance of denudation, both B and E assume importance, with the result that still newer deposits B′ and E′ are evolved. Similarly A and D contribute the deposits A′ and D′ respectively. Ultimately vertical sections in the newly-formed deposits will disclose successions as indicated in the diagram (*Fig.* 28), bC′, aB′, eF′ and dE′ being the transitional zones from one horizon to another.

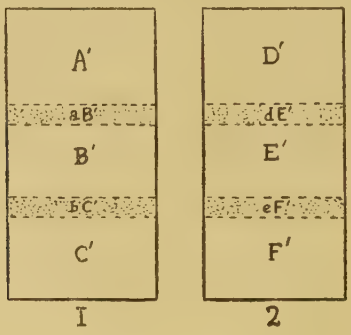


Fig. 28.

The above, however, does not take into account the probable intermingling of sediments due to lateral distribution, for instance, by marine currents; such intermixing will tend in a definite direc-

tion, viz., that of the prevalent current. Supposing this direction to be from the first to the second province, parallel to the shore-line as shown in the diagram (*Fig.* 29), then while the sedimen-

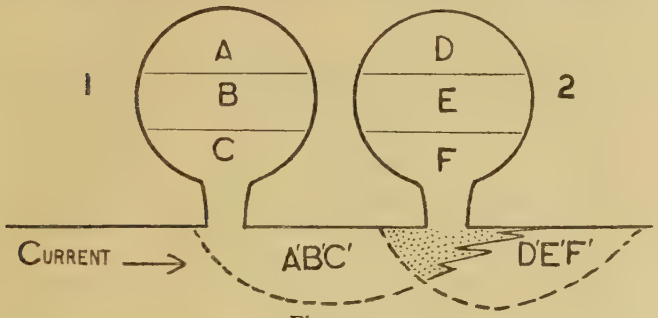


Fig. 29.

tary series A′—C′ would preserve local individuality, their lateral displacement due to the current would cause contamination of and interdigitation with the series D′—F′, indicated by the shaded area in the figure. Thus in specific cases the composition of the mixed sediments might be represented by c′F′, b′E′, etc., c′ and b′ connoting the introduction of material from the first province. Save in small land-locked areas of deposition, such contamination will usually be of widespread occurrence, and will result in the production of sedimentary phases, each involving a very general (regional) type of " heavy " residue. At certain points, however, where deposition is initially concentrated, as in the cases cited above, local changes in composition will be found, represented by a possible influx of one or two new species, the flooding of a particular species, or by marked change in physical character of the constituent particles.

It follows from this that over limited areas of sedimentation a given deposit may preserve petrographic features broadly differentiating it from older or younger formations, and under such circumstances the intensive study of the petrography of the deposit may be of direct stratigraphical import, especially if palæontological evidence is poor. It must not be inferred from this, however, that in the occurrence of a mineral suite characteristic of a given sediment, we have an infallible index of correlative value. Correlation by means of " heavy " residues, as will subsequently be shown, must be, from its very nature, an extremely restricted method and only applicable under very limited and precise conditions; even then cases arise in which the practice is rendered extremely difficult by petrographic or tectonic anomalies, mention of which will be made ultimately.

As examples of mineral residues broadly distinctive of particular formations, we may cite those characteristic of the Lower Greensand contrasted with those of the Wealden Sands in the Weald of England, or the assemblages characteristic of the Pliocene formations contrasted with those of the Eocene deposits mentioned by Professor Boswell [8]. In the case of the Wealden Sands the author has been able to discriminate between the Ashdown and Tunbridge Wells members of the Hastings Sands Series by their distinctive assemblages [60], such differentiation being an invaluable aid to mapping in the field where the two formations, frequently exhibiting such marked lithological similarities, are brought into juxtaposition by faulting.

Again, recent petrographical work has proved the contemporaneity of certain unfossiliferous deposits occurring as outliers in western Cornwall, which by mere lithological resemblance

to the well-known Pliocene beds of St. Erth, had been hitherto doubtfully assigned to that period of deposition [56].

And so cases could be multiplied, all tending to indicate that the ultimate recognition of mineral assemblages peculiar to given strata is of pertinent stratigraphical value, in no way antagonistic, but rather directly complementary to palæontological evidence.

Local correlation of horizons or definite lithological planes within a given series is a more specialised development of the broader methods and calls for higher technique in the discrimination of petrographical characters, enabling the requisite distinctions to be made. Over comparatively small areas, say within 400 square miles, a given mineral assemblage so frequently assumes marked constancy in crystallographic, physical and optical properties as to render possible its differentiation and segregation from superincumbent or subjacent suites. Such constancy is strikingly independent of the lithology of the beds, the same residue being characteristic of sand, silt and clay—if the three facies are present—the only differences noted being those attributable to natural mechanical grading of the particles. On the other hand, when traced vertically (*i.e.*, time range), slight differences are often appreciable if not in composition, frequently in the physical character of residues; such dissimilarities when recognisable have distinct differential (hence correlative) significance.

Ability to detect the small discordances between mineral suites constitutes the criterion by which precision is obtained in petrographic methods, and it must be said that considerable experience is necessary with all types of residue before the finer distinctions can be appreciated and drawn.

[Fig. 30.] MINERAL DETERMINATION SHEET. No.....

Convention: "Flood" 9, Very Abundant 8, Abundant 7, Very Common 6, Common 5, Scarce 4, Very Scarce 3, Rare 2, Very Rare 1.

Sample No															
Minerals. Anatase.															
Andalusite.															
Apatite.															
Augite.															
Barytes.															
Biotite.															
Brookite.															
Calcite.															
Cassiterite.															
Chalcedony.															
Chalybite.															
Chlorite.															
Chromite.															
Columbite.															
Cordierite.															
Corundum.															
Diamond.															
Epidote.															
Fluorite.															
Garnet.															
Glauconite.															
Glaucophane.															
Gold.															
Gypsum.															

Kaolinite.																
Kyanite.																
Leucoxene.																
Limonite.																
Marcasite.																
Magnetite.																
Microcline.																
Monazite.																
Muscovite.																
Olivine.																
Orthoclase.																
Plagioclase.																
Pyrites.																
Pyrolusite.																
Pyrrhotite.																
Quartz.																
Rutile.																
Sillimanite.																
Sphene.																
Spinel.																
Staurolite.																
Topaz.																
Tourmaline.																
Wolframite.																
Xenotime.																
Zircon.																

Under these circumstances it is difficult, if not impossible, to lay down hard and fast rules applicable to all cases of correlation, but the following scheme may be of service to the student, to be elaborated or remodelled as further research in sedimentary petrography dictates.

Apart from the mere identification of the minerals present, correlation of sediments by petrographic methods involves three important determinations :—

(1) The frequency of occurrence of individual species.

(2) The persistence of each species, *i.e.*, lateral and vertical distribution, chiefly the former.

(3) Constancy or inconstancy of mineralogical features of species throughout.

(1) The frequency of occurrence of the several species is essentially a quantitative factor deducible from a careful study of each sample under investigation. It implies the expression of relative proportions of the several minerals occurring in the sample, and is therefore to a certain extent governed by the apportioning powers of the observer. It is unfortunate that no standard can be set whereby the relative frequency of a given species can be definitely expressed; short of actually counting the grains, this seems to be an impossibility. Hitherto investigators have been content to use the words " abundant " or " preponderant," " common," " scarce " and " rare " as connoting the degree of frequency, in some cases qualified by the word "very" where emphasis is required. Symbols a, A, etc., representing " abundant," " very abunant," may better be replaced by figures, as the mental picture conveyed by comparison of figures rather than of letters of the alphabet is a decided

advantage for correlation purposes. The author, in addition, uses the word "flood" when a particular species is so far in excess of all others as to constitute almost a pure concentrate.

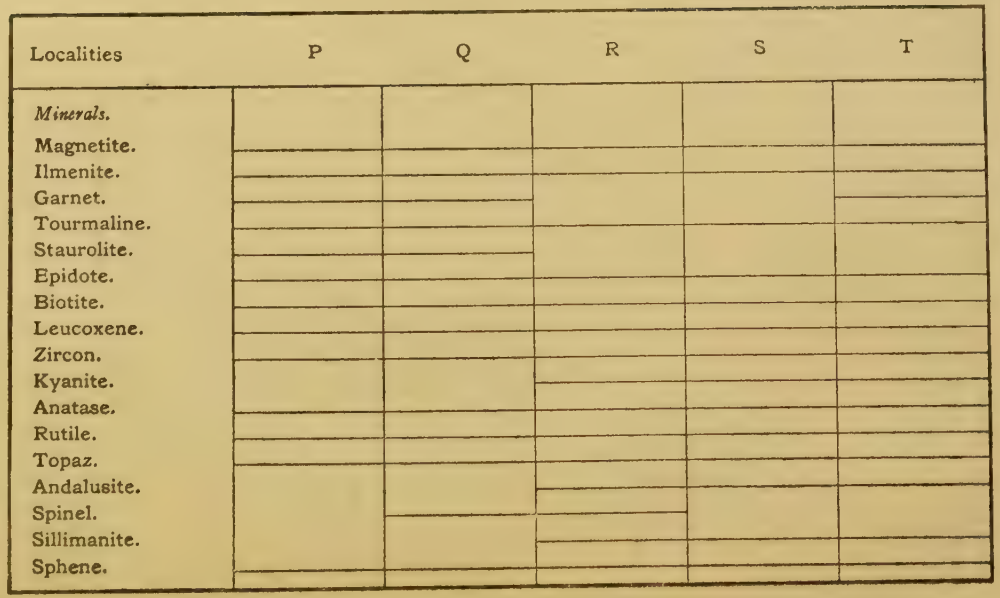
Term.	*Symbol.*	*Proposed Number.*
"Flood"	F	9
Very Abundant	A	8
Abundant	a	7
Very Common	C	6
Common	c	5
Scarce	s	4
Very Scarce	S	3
Rare	r	2
Very Rare	R	1

It will be found that a rough check to the accuracy of the determination may be made by counting the number of grains of each species in (say) four different fields, and comparing the relative proportions in each case; from this and an inspection of the whole slide, the relative frequency of species may be obtained. A specimen determination sheet is appended (Fig. 30).

Samples in which the frequency factors present similarity may be grouped together at the outset, their ultimate relationship or otherwise being confirmed by subsequent investigations under (2) and (3). The average composition of the group should also be determined, as this facilitates the comparison of one group or assemblage with another.

(2) The persistence of individual minerals connotes their uniform or sporadic distribution, and is an important factor, especially in problems of areal correlation. Such persistence may be expressed in terms of distance from one locality to another, or in the case of a small area where quarries, pits or well-

[Fig. 31.] PERSISTENCE DIAGRAM



borings yield the evidence, for example, from point to point as dictated by circumstances. It is desirable to construct a persistence diagram for reference in this connexion, and further to estimate the percentage of species which are actually persistent throughout; if this percentage is high (say over 60%) such an estimate may be of great significance. *Fig.* 31 shows the type of persistence diagram usually employed.

(3) The constancy of mineralogical characteristics of the minerals involves a detailed study of the crystallographic, physical and optical properties of the same species met with in different samples. This study necessitates the greatest care and exactitude in observation, and calls for the exercise of that technical ability only gained by long and patient investigation of detrital grains.

Comparing grains of a mineral such as tourmaline for example, their crystallographic characters involve the presence or absence of crystalline form, structure and habit; their physical properties comprise colour, lustre, cleavage, fracture, parting and degree of abrasion (a function of hardness); their optical properties involve principally refractive index, birefringence and pleochroism. Crystallographically two forms may possibly occur, prismatic and basal grains; physically, one or more prevailing colours may be seen in the grains, possibly blue and brown (one predominant), while cleavage and parting being absent, the fracture may be noted as uneven or conchoidal, and the degree of abrasion expressed as subangular or rounded as the case may be; optically, certain properties will be significant, especially the degree of pleochroism of the prismatic grains and the prevalence of basal grains yielding characteristic uniaxial interference figures.

The greater the degree of similarity of all these properties noted in the successive grains studied, not only of tourmaline, but of other species present, the greater is the probability that the samples to which they pertain are representative of one and the same deposit, if not actually of a definite horizon within that deposit.

We may further note certain minerals which are often specifically useful for purposes of correlation, more particularly on account of the variation possible in their physical and optical properties, one facies often being peculiar to a given phase of sedimentation; such variation is a function of the intensity of mechanical stress on the one hand, and of the nature of the parent rock on the other. The species are tourmaline, staurolite, epidote, kyanite, zircon, andalusite, topaz, rutile, anatase and quartz. The marked variations in the pleochroism and colour of tourmaline, in the form, pleochroism, nature and number of inclusions in staurolite, in the cleavage fragments of kyanite, and in the red pleochroism of andalusite (if developed), to cite only four of those minerals, constitute factors whereby discrimination may be made on the basis of the degree of individualism thus accorded to the species concerned, hence to the group to which they belong.

It must not be inferred from the foregoing paragraph that minerals other than those mentioned are of subordinate correlative value; frequently it happens that the presence of a scarce mineral such as glaucophane, monazite or gold, by persistence in distribution and uniformity of character, turns the scale in favour of grouping together those samples in which it occurs, while in another case the surprising persistence of geniculate twins of crimson rutile may suggest a possible relationship.

The cumulative evidence resulting from the in-

tensive study of " heavy " residues as outlined will suggest the most likely and accurate grouping of the mineral assemblages, hence the basis of linear and vertical correlation. In addition, the differences presented by the lighter constituents of the samples, such as quartz, felspar, glauconite and authigenous minerals must be noted, and where possible used to supplement the more detailed evidence accruing from that study.

Other evidence for correlation of heavy mineral suites may be obtained from comparison of the sizes of grains of the same species, and also of the percentages of total " heavy " residue in a series of samples, calculated in the manner suggested in Chapter I. In the first case a certain amount of information is obtained from the initial mechanical grading of the sample, whether by rough sieving or more accurately by elutriation. In the latter connexion the classification of the size of grains adopted by Professor Boswell [12] is the most satisfactory and may be quoted here :—

G.	> 2 mm. diam.			Gravel (G).	
VCS.	> 1 mm.	,, and < 2 mm.		Very coarse sand.	
CS.	> 0.5 mm.	,, ,,	< 1 mm.	Coarse sand.	Sand grade (S).
MS.	> 0.25 mm.	,, ,,	< 0.5 mm.	Medium sand.	
FS.	> 0.1 mm.	,, ,,	< 0.25 mm.	Fine sand.	
s.	> 0.05 mm.	,, ,,	< 0.1 mm.	Superfine sand or coarse silt.	Silt grade (s).
	> 0.01 mm.	,, ,,	< 0.05 mm.	Silt.	
c.	< 0.01 mm.	,, ,,		Clay or mud grade (c).	

His method of expressing the mechanical analyses of samples is as follows :—

VCS	CS	MS	FS	s	c	S
11.8	44.1	41.5	2.2	0.2	0.2	99.6

where the numbers represent percentages by weight of the various grades, S being the total sand grade.

For purposes of correlation, inferences may be drawn from the comparison of the total sand grades of different samples or, if necessary, of any particular grade which may predominate. It is hardly necessary to add that where such mechanical analyses can be made and used in addition to the qualitative data obtainable from microscopical investigation, the accuracy of correlation is greatly enhanced.

The actual size of individual grains may be obtained microscopically by using the ordinary micrometer eyepiece, taking into account the magnification of the objective employed. For instance, in this way a series of topaz grains, each measuring between 0.1 and 0.3 mm. in greatest length, may be of utility in tracing out horizons within narrow limits.

Finally, the comparison of percentage residues for different samples affords further evidence, more especially for broad correlation. It is found that for a given stratum the percentage of heavy mineral concentrate obtainable is remarkably uniform within narrow limits, and consequently the initial quantitative estimation is always recommended [60].

Having outlined the methods whereby problems of areal and of local correlation may be attacked, it remains to notice certain cases in which difficulties or anomalies may arise to impede the progress of investigation.

Firstly, we may consider the case of unconformability of strata. Professor Boswell has remarked that " unconformities are usually emphasised by the changes in mineral composition, and these support palæontological and field evidence " [8]. Broadly speaking this is true, but frequently local erosion has been such, that what is

theoretically conceived as the plane of unconformity, is in reality a zone of unconformity, *i.e.*, an indefinite thickness of sediment, the combined product of contemporaneous erosion and deposition, with a mineralogical composition having affinities with both the older and the younger deposits.

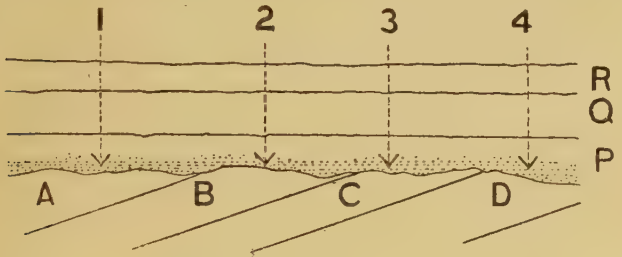


Fig. 32.

Thus, if a series of samples is taken laterally from the points 1, 2, 3, 4 (*Fig.* 32), the material collected will be from a " mixed " zone (dotted), and the mineralogical composition may be represented as follows :—

Sample 1.....ap.
Sample 2.....bp.
Sample 3.....cp.
Sample 4.....dp.

} The small letters are indicative of transitional variations in composition from A to P, B to P, etc.

Accordingly, lateral variation at approximately the same horizon becomes pronounced under these circumstances, and where such a structure is hidden (as it may well be in petroliferous territory which is being explored by the drill), a false impression can easily be drawn from the discordances between the " heavy " residues, structural interpretation suffering in consequence. The mitigating factor in this case is the tendency for " flooding " of a particular species to occur wherever different beds are

subjacent to P, and consequently the four samples should each present this feature. The reason for such a tendency to " flooding " is that the actual process of differential erosion of the tilted edges of A, B, C and D tends to eliminate the less stable and gradually concentrate the more stable minerals in any undulations created; the material then becomes mixed with newly deposited sediment, and in this way not only is the " mixed " zone initiated, but the proportion of " heavy " minerals greatly increased, with probable concomitant " flooding " of one or more species. It is a noteworthy fact that such " flooding," especially of minerals like zircon, kyanite and magnetite, is often characteristic of sediments involved within the zone of unconformity.

Another difficulty, and one which is far more fundamental, arises out of Professor Boswell's recent discussion on the transgression of time-planes by lithologic planes [15]. The theoretical progression of lithological facies laid down on a continental shelf is from coarse to fine material, the grade size of the constituent particles decreasing with depth of water in which they are deposited. This conception normally assumes a static condition of the sea-floor. Frequently, however, gradual upheaval or subsidence of the basin is manifest, with the result that the interpretation of the record of sedimentation from the subsequently consolidated deposits is apt to be erroneous, if formulated on purely lithological grounds. The transgression of time-planes, *i.e.*, successive phases of sedimentation or bedding planes, by lithologic planes, *i.e.*, successive facies of deposition, is a direct result of one or other of those movements operative during sedimentation. In the case of subsidence, the vertical thickness of the deposits is accentuated, while

in the case of elevation, the lateral or seaward spread of the detritus is increased. In both cases definite facies such as sands, silts and clays are in juxtaposition when traced from one time-plane to another, so that ultimately when the deposits are consolidated, the tendency is for them to be differentiated on lithological grounds as true bedding planes, which is obviously fallacious. In tracing the mineral assemblage characteristic of the clay facies, for example, a variation will tend to occur in the residues as each successive time-plane is traversed, so that lateral correlation of the clay will be a matter of considerable difficulty. If, however, comprehensive sampling of the sand and silt grades associated with the clay is carried out, careful observation will detect a mineral suite characteristic of and common to the sand, silt and clay components of each successive time-plane, and thus a clue gained to the real state of affairs. It is essentially the tendency, already noted (p. 91), of an inherent mineral assemblage to persist throughout a definite phase of deposition (involving change of lithological facies with progressively deeper water), that makes possible a correct interpretation of the true sequence of events. From what has been said, however, it must be apparent that for accurate petrographic work in such circumstances, it is imperative to have some broad idea of the tectonics of the area under consideration. Further, the investigation of any particular series of beds demands a knowledge of the petrography of both older and younger formations occurring in the same district, a point that cannot be over emphasised, not only in difficult cases such as those cited above but in all phases of correlation by means of exclusive mineral assemblages.

CHAPTER IV.

THE BEARING OF SEDIMENTARY PETROGRAPHY ON PALÆOGEOGRAPHICAL PROBLEMS.

Although for some purposes it may be sufficient simply to effect the qualitative and quantitative examination of a deposit, geologically speaking the investigation is incomplete without carrying the inquiry still further, viz., to a consideration of the source or sources of origin of the material, and its bearing on the palæogeography of the area at the time of deposition. The perusal of this more philosophical aspect of the science is not merely academic; indeed, one might almost say that without such an inquiry all petrographic work must lose both in precision and value: it will certainly lack vitality. As an aid to problems of correlation on the lines discussed in the last chapter, such research is of fundamental importance.

The tracing of a parent source of the constituent particles of a deposit is often by no means a straightforward matter, especially where the locale of a distributive province capable of furnishing the material, is obscure, or where, owing to widespread erosion, no direct evidence of such a province exists. The problems to be faced are, from their very nature, some of the most complex and absorbing that a geologist has to solve, and each case must perforce be dealt with on its own merits. Accordingly we cannot presume to do more than

indicate here certain broad factors to be taken into account in all considerations of this character, leaving it to the initiative and ability of the investigator to evolve the more detailed plan likely to lead to the most reasonable conclusions in the particular case with which he is concerned.

The mineralogical analysis of a deposit will show a certain suite of detrital grains which may or may not be suggestive of the source of origin, either individually or collectively. Generally speaking, there is seldom an instance where the petrographer fails to gain some clue, however small, to the source of some at least of the species represented. In the descriptions of the detrital minerals given in Chaper II, possible sources of origin of the several species are included to enable an initial estimate to be made; this information, however, only applies to individual grains. Paragenesis is just as important a factor in detrital sediments as in igneous or metamorphic rocks, and more often than not the indication of the source of origin of the deposits comes from the association of species noted, rather than from particular grains.

The association of sillimanite, kyanite, andalusite and garnet, or again, a garnet-staurolite-kyanite suite, are both suggestive of derivation from a definite thermo-metamorphic province, just as a sphene, apatite and zircon assemblage (if marked) is indicative of acid or intermediate rock-types as possible sources of supply. The characteristic association of ilmenite, anatase, rutile and brookite (the last three probably secondary), often with pleonaste and possibly pyrope in addition, points to derivation from basic or ultrabasic rock-types, while the prevalence of cassiterite, topaz, wolframite and rare-earth minerals in certain alluvials may be equally suggestive of their primary

environment. On the other hand, a predominance of the more stable minerals such as zircon, tourmaline, rutile and iron ores, probably to the total exclusion of such other species as are mentioned above, implies derivation from pre-existing sediments, and in such cases the location of the ultimate source of origin is rendered considerably more difficult.

The lithology of the deposit as a whole must be taken into account of all investigations of this nature; if present, boulders, pebbles or the constituent fragments composing the " gravel " grade should be closely examined as regards their form and composition. We may cite the instance of the Lower Greensand of N.W. Wiltshire in this connexion, where, in addition to a very characteristic mineral suite, the included water-worn pebbles of quartz, limestone, chert, and slate are valuable indices both of mode of deposition and source of derivation. The occurrence of subangular pebbles of cassiterite, schorl and metamorphosed Devonian slate in the Pliocene sands of St. Agnes, Cornwall, leaves no room for doubt as to the local derivation of the beds, quite apart from their convincing " heavy " mineral assemblage. Professor's Bonney's work on the Bunter Pebble-Beds of the Midlands [4] and Dr. Gilligan's investigations of the pebbles of the Millstone Grit of Yorkshire [36] are yet further instances of the value of careful study of the coarser material of sedimentary rocks. We may note also the researches of Dr. Mackie on the inclusions present in quartz occurring in various rocks in Scotland, wherein he has shown that a critical examination of the inclusions in detrital quartz grains may have a direct bearing on the source of derivation of the sediment in which they occur [55].

It frequently happens that a particular mineral will, by its form, colour or other specific character, betray its source of origin from strong resemblance to the same species known to occur in older rocks; this is specially the case with younger sediments which have in part been derived from the breaking up of pre-existing detritus. In this way a flood of light may be thrown not only on the direction and mode of transport, but also on the physiographical conditions prevalent at the time of deposition. Dr. H. H. Thomas has traced the staurolite occurring in the Bunter Pebble Bed of south-west England to the Armorican massif (or its more northerly extension in Triassic times), hence the prevalent flow of sediment-bearing currents from the south [76]. The author's work on the Pliocene deposits of Cornwall has shown that the staurolite occurring in these deposits has had the same derivation, while the presence of Lower Cretaceous types of kyanite in the most northerly localities has suggested the flow of sediment-bearing rivers from the north-east, *i.e.*, from the region in which, in Pliocene times, the main mass of Cretaceous rocks were extant [59]. Again, in view of Dr. Mackie's researches on the accessory minerals of Scottish granites, in which he proved the occurrence of monazite in 43 out of 52 examples examined [36], the presence of this species in the Millstone Grit of Yorkshire is a strong argument in favour of Dr. Gilligan's contention that that deposit had a northerly derivation.

In working out problems of this nature, therefore, it is advisable firstly to note the possible types of rocks from which each mineral species may have been derived, and secondly to investigate the presence (or absence) of such types within a given region capable of furnishing the material. In this

way palæogeographical questions arise collaterally, and the unravelling of the geological record within the limits of the periods represented by both parent rock and sedimentary deposit constitutes the crux of the whole matter.

Palæogeographical restoration to be complete and accurate necessitates a very detailed knowledge of regional stratigraphy and also the absence of imperfections in the geological record. The former may be acquired by the geologist as a result of detailed work—in fact its realisation is a *sine quâ non* to the successful prosecution of all petrographic work. The latter is largely a matter of chance, and naturally varies in different districts. Obviously the more faithfully the history of past geological events is chronicled by the rocks, the more complete is the stratigraphical record, and solutions to problems of geographical reconstruction are facilitated accordingly. If, in this connexion, we compare south-east with south-west England, it is at once apparent that palæogeographical investigations in the former, where there are few gaps within the limiting series as developed, are much more straightforward than in the latter region, where no evidence whatever is preserved of the trend of events between late Palæozoic and early Tertiary times.

Again, the evidence of organic remains (where these are preserved) must obviously play a fundamental part in inquiries of this nature; only where palæontological investigations are followed hand-in-hand with petrographical analysis can we expect to gain the fullest knowledge, enabling each step in the process of reconstruction to be made with a reasonable degree of accuracy.

The bearing of certain detrital grains on questions concerning climatic conditions prevalent at the

epoch of deposition has received a good deal of attention from various observers. Under certain conditions the evidence afforded is convincing, especially in the case of felspar grains, but frequently it must be admitted that the indications are inconclusive. As early as 1886 Judd described the freshness of the felspar grains of the Nile deposits as indicative of mechanical disintegration and desert conditions, *i.e.*, tropical heat by day and rapid cooling by radiation at night.† Medlicott and Blandford,* of the Indian Geological Survey, have drawn attention to differentiation of altered and unaltered felspar grains, the former as indicative of mechanical attrition, the latter of chemical weathering; in this way felspar grains present in the Siwalik deposits and also in the Indo-Gangetic alluvium, are referred to the breaking down of the parent rocks by ice and frost, since they are remarkably fresh and unaltered.

Dr. Mackie's paper on "Felspars in Sedimentary Rocks as Indicators of Climate" [56] is another instance of detailed research in the differentiation of fresh and altered felspar grains as criteria of mode of attrition, hence of prevalent climatic conditions. Where alteration is very marked, the inference to be drawn is that moist and humid conditions prevailed, tending to promote chemical decay; where freshness of felspar is the marked feature, mechanical attrition under arid or glacial conditions is suggested, and in such cases a decision must be made between the one or the other by general stratigraphical and lithological evidence; the marked angularity of grain character-

† Proc. Roy. Soc., vol. xxxix., 1886, pp. 215, 217.
* Manual of the Geology of India, 2nd Ed., 1893, p. 201.

istic of glacial deposits, usually contrasts in a striking manner with the strong tendency to rounding exhibited by æolian detritus.

Dr. Gilligan's researches in connexion with the conditions attendant on the deposition of the Millstone Grit, indicate a prevalent monsoon type of climate, by which heavy rains, capable of feeding large rivers, were maintained; hence the weathering of the material was preponderantly mechanical, as evidenced also by the character of the grains and particularly by the "exceeding freshness of the felspars" [36].

The more detailed study of detrital grains has served to show that not only felspar, but also minerals like staurolite, andalusite and kyanite may be indirectly indicative of climatic conditions, partly from observations of their degree of alteration, and partly from considerations as to their ultimate origin. In the Pliocene deposits of Cornwall the staurolite grains preserve a subangularity entirely consistent with marine transport; their source of origin from the south-west is suggestive of prevalent currents from that direction, thus reflecting present-day conditions. Confirmatory evidence of this is to be found in the location of the Pliocene outlier at St. Agnes on the leeward side of St. Agnes Beacon (N.E.), and by comparison with prevailing climatic conditions of Cornwall to-day, where heavy rains are wont to accompany south-west winds, we may infer, with a reasonable degree of accuracy, somewhat similar conditions operative in early Pliocene times.

The evidence afforded by andalusite is rather more obscure, but a study of the mineral shows that there are two distinct types of weathering, one characteristic of the species derived from contact metamorphic rocks, the other characteristic of grains

derived from andalusite-bearing granites. In the former case the degree of alteration is usually far more advanced than in the latter instance; sericite, kaolin and possibly chloritic matter may be so prevalent as to cloud the grain entirely, particularly under climatic conditions favourable to intensive chemical weathering. This will, of course, to a certain extent, apply to grains derived from granitic rocks under similar conditions, but it is a noteworthy fact that where this source of the mineral is determined, its freshness and form are clearly indicative of mechanical disintegration, generally under rather frigid climatic conditions.

Attention has elsewhere been drawn to the problems presented by the restricted distribution of andalusite (p. 31). It is the author's belief that a fuller knowledge of this mineral is necessary as evidence relevant to cases such as are under discussion.

Thus is reviewed the more theoretical potentialities of comprehensive petrographic work. Enough has been written to show that in the present state of our knowledge, while we may realise the extent and importance of the problems presented by a study of detrital sediments, there remains an enormous amount of work to be done before Professor Marr's "geogram" of a deposit can be accurately visualised. The whole subject is in its infancy, and it offers to the research student some of the most fascinating problems in philosophical geology. The Natural History of Sedimentary Rocks has yet to be written, but at present the data for such a treatise are incomplete.

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FIG. 33.

DISTRIBUTION OF THE CHIEF DETRITAL AND ASSOCIATED MINERALS IN CERTAIN BRITISH STRATA.

DISTRIBUTION OF THE CHIEF DETRITAL
CERTAIN BRI

PERIOD	HORIZON	LOCALITY	ANATASE	ANDALUSITE	APATITE	AUGITE	BARYTES	BIOTITE	BROOKITE	CALCITE	CASSITERITE	CHALCEDONY	CHALYBITE	CHLORITE	CHROMITE	COLUMBITE	CORDIERITE	CORUNDUM	DIAMOND
RECENT	SHORE SAND	ST IVES, CORNWALL.		+				+			+		+	+					
PLEISTOCENE	LOAM IN GRAVEL	CROYDON.	+	+	+	+												+	
?	CLAY WITH FLINTS	WALTON HEATH.		+							+								
?	HEADLEY HEATH SAND	HEADLEY HEATH, SURREY		+															
PLEISTOCENE	NORTH SEA DRIFT	SUFFOLK.	+	+				+											
PLIOCENE	LOWER PLIOCENE	ST ERTH, CORNWALL.	+	+				+	+		+			+				+	
d.o	BOXSTONES	SUFFOLK.		+	+					+									
EOCENE	BAGSHOT SAND	HAMPSTEAD, LONDON.																	
do.	do	BARTON, HANTS.																	
do.	LONDON CLAY	EAST ANGLIA.	+		+	+		+											
do.	BLACKHEATH BEDS	HAYES, MIDDLESEX.		+	+			+											
do.	WOOLWICH BEDS	IPSWICH.	+		+	+												+	
do	THANET SANDS	EAST ANGLIA.	+		+	+		+						+					
CRETACEOUS	UPPER CHALK	DOWNE, KENT.																	
do.	MIDDLE CHALK	BEER HEAD, DEVON.	?	+				+				+		+					
do	UPPER GREENSAND	GODSTONE, SURREY.						+											
do.	GAULT	MERSTHAM, SURREY.								+									
do	AYLESBURY SAND	STONE, BUCKS.																	
do.	SANDRINGHAM SAND	NORFOLK.				+		+											
do.	FOLKESTONE BEDS	REIGATE, SURREY.		+															
do.	SANDGATE BEDS	NUTFIELD, SURREY			+		+												
do	HYTHE BEDS	TILBURSTOW HILL																	
do.	ATHERFIELD CLAY	WOODHATCH, SURREY.								+		+							
do.	WEALD CLAY	do.					+												
do	TUNBRIDGE WELLS SAND	ASHHURSTWOOD, SUSSEX.	+																
do	ASHDOWN SANDS	HASTINGS.																	
JURASSIC	KELLAWAYS ROCK	BURYTHORPE, YORKS.																	
do	UPPER ESTUARINE	YORKSHIRE.																	
do	INFERIOR OOLITE	NORTHANTS.	+																
TRIASSIC	KEUPER MARL	LEICESTERSHIRE.	+				+	+											
do.	do.	BUDLEIGH SALTERTON.	+					+	+					+			+		
do.	BUNTER PEBBLE BED	DEVON.	+		+			+	+		+						+		
do.	LOWER BUNTER	WORKSOP, NOTTS.			+														
PERMIAN	LOWER SANDSTONE	DEVON.	+											+					
do.	LOWER PERMIAN	YORKSHIRE.	+		+			+											
CARBONIFEROUS	COAL MEASURES	N OF ENGLAND.	+					+						+					
do.	MILLSTONE GRIT	SCOTLAND.	+																
do.	do.	YORKSHIRE.	+	+			+		+	+									
do	CARBONIFEROUS LST.	SCOTLAND.	+																
PRE-CAMBRIAN	TORRIDON SANDSTONE	do.						+											

ND ASSOCIATED MINERALS IN STRATA

GARNET	GLAUCONITE	GLAUCOPHANE	GOLD	GYPSUM	HAEMATITE	HORNBLENDE	HYPERSTHENE	ILMENITE	KAOLINITE	KYANITE	LEUCOXENE	LIMONITE	MAGNETITE	MARCASITE	MICROCLINE	MONAZITE	MUSCOVITE	OLIVINE	ORTHOCLASE	PLAGIOCLASE	PYRITES	PYROLUSITE	PYRRHOTITE	QUARTZ	RUTILE	SILLIMANITE	SPHENE	SPINEL	STAUROLITE	TOPAZ	TOURMALINE	WOLFRAMITE	XENOTIME	ZIRCON
+					+																			+				+						+
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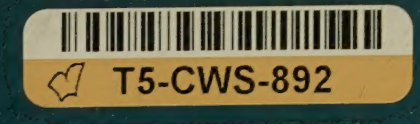
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